Pediatric Robotic Urology

Edited by

Jeffrey S. Palmer

Humana Press

PEDIATRIC ROBOTIC UROLOGY

CURRENT CLICICAL UROLOGY

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To my parents, whose love, support, dedication and sacrifices have enabled their children to be the best that they could become. I thank them both.

-Jeffrey S. Palmer

Preface

Laparoscopic surgery has been instrumental in the advancement of minimally invasive surgery in the adult patient with urologic conditions. Robotic-assisted laparoscopic surgery has allowed the urologic surgeon to perform more advanced laparoscopy operations in the adult patient. Radical prostatectomy is a perfect example. Although laparoscopy has been utilized for several decades in children for the diagnosis and treatment of undescended testicles and ambiguous genitalia, robotic technology has been slower to advance into the pediatric arena compared to the adult.

However, the use of robotic technology in recent years for the pediatric urologic population has gained momentum. The intuitive nature of robotic-assisted laparoscopy compared to conventional laparoscopy allows for the relative novice to perform fine surgical techniques, such as suturing, with more ease and dexterity. One robotic-assisted operation that is more commonly being performed in the pediatric population is pyeloplasty with more advanced procedures such as bladder augmentation and ureteral reimplantation also being performed by the more experienced surgeon.

Pediatric Robotic Urology, a concise and comprehensive reference on robotic-assisted laparoscopy, is written specifically for surgeons and other health care providers caring for the pediatric urologic patient. Well-respected surgeons have been carefully chosen to author the chapters due to their expertise in laparoscopic urologic surgery. The basics of laparoscopy and robotic-assisted laparoscopy will be discussed along with specific surgical techniques which will be accompanied with illustrations and intraoperative photographs. The chapters are arranged into two sections to allow for easier access to the information: Introductory topics and surgical techniques. Upon completion of this text, it is my sincere hope that the reader will learn the basic and advanced robotic-assisted surgical techniques to assist them in the care of children.

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                                                                    August 2009

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Urologic Laparoscopic Anatomy

Kevin M. Feber and Lane S. Palmer

Abstract Laparoscopy, and particularly robotically assisted laparoscopy, continues to advance rapidly, thus changing the practice of urology. The changes in the practice of pediatric urology, while slower, have also altered the surgical approach to various conditions of the genitourinary tract in children. While open procedure typically require a thorough working knowledge of smaller areas, the laparoscopic surgeon must have a thorough working knowledge of the entire abdomen and pelvis as they are in full view for all cases. In this chapter, we aim to provide the reader with the anatomic perspective associated with our new paradigm in surgical care.

Keywords Anatomy · Robotic · Laparoscopy · Urology · Children

1. INTRODUCTION

The practice of urology has been ever changed with the advent of laparoscopy and robotically assisted laparoscopy. In adult urology practice there is a paradigm shift currently underway in the surgical extirpation of renal tumors *(1)* and prostate cancer *(2)*. Changes in clinical practice extend to pediatric urology in the surgical approach to many of the congenital disorders that we treat (Table 1) *(3)*. The laparoscopic perspective, with or without the surgical robot, to the disorders of the kidney, ureter, bladder, nonpalpable testes, and intersex is markedly different from the open surgical approach since the visual perspective is from above and from the abdomen rather than from the flank, groin, pelvis, etc. In some instances, the camera will be placed in different ports during the same case which changes the perspective of the surgical field and the surgical anatomy. Since the anatomic view is quite different, it is imperative for the pediatric urologic surgeon to know and master this perspective. In this chapter, we aim to provide the reader with the anatomic perspective associated with our new paradigm in surgical care.

Table 1
**Robotically Assisted Laparoscopic Urologic
Procedures in Children**

Kidney
  Nephrectomy
  Partial nephrectomy
  Nephreoureterectomy
  Renal cyst decortication
  Nephrolithotomy
  Pyeloplasty

Adrenal
  Adrenalectomy

Bladder
  Ureteral reimplantation
    Extravesical
    Transvesical
  Bladder augmentation
  Autoaugmentation
  Cystolithotomy
  Urachal excision
  Appendicovesicostomy

Gonadal/Spermatic Cord
  Varicocelectomy
  Orchidopexy
  Excision of ovarian cyst
  Gonadal biopsy

Other
  Lymphadenectomy
    Renal
    Retroperitoneal
    Pelvic
  Excision seminal vesical cyst
  Excision Müllerian remnant

2. ADRENAL GLANDS

The adrenal glands are paired structures which reside in the intermediate pararenal compartment of the retroperitoneum. They are encased in Gerota's fascia and separated from the upper pole of the kidney by a thin layer of connective tissue. They weigh 5–7 g and transversely are 3–5 cm in greatest dimension. The adrenal glands can be differentiated from the surrounding adipose tissue by their yellow–orange color. Since the adrenal glands have a different embryologic development from the kidneys, they remain in their normal location in cases of renal ectopy or absence. The right adrenal gland has a pyramidal shape and is positioned more

superiorly in the retroperitoneum. It is located directly above the upper pole of the right kidney, medial and posterior to the liver, lateral and posterior to the duodenum and lateral to the vena cava. The left adrenal gland lies medial to the upper pole of the left kidney and has a more crescenteric shape. The splenic vessels, tail of the pancreas, and stomach are all located anteriorly and superiorly.

The adrenal gland consists of an inner medulla and an outer cortex. Ninety percent of the adrenal gland comprises the cortex which has a mesodermal origin. The cortex consists of an outer layer, the zona glomerulosa which produces aldosterone, a middle layer, the zona fasiculata which produces cortisol, and an inner layer, the zona reticularis which produces the andro-gen, dehydoepiandrosterone. The adrenal medulla, derived from neural crest cells consists of chromaffin cells. The sympathetic chain sends presynaptic sympathetic nerve fibers to directly innervate the medulla. Sympathetic stimulation releases norepinephrine, epinephrine, and dopamine.

The adrenal gland has a single venous drainage and an arterial supply that arises from three sources. The inferior phrenic artery comes from the aorta and provides the superior blood supply. The aorta sends branches to comprise the middle arterial blood supply. The most inferior blood supply comes from the ipsilateral renal artery. Each adrenal gland is drained by a single adrenal vein. The right adrenal vein empties directly into the vena cava on the posterior and lateral side. The left adrenal vein is joined by the inferior phrenic vein and both enter the left renal vein superiorly opposite the gonadal vein. The adrenal glands send lymphatic drainage into the para-aortic lymph nodes via lymphatics that parallel the venous drainage.

The adrenal glands can be approached by either a retroperitoneal or transperitoneal approach. Since transperitoneal robotic surgery is currently favored, we will limit our discussion to this anatomic approach. In the transperitoneal approach to the left adrenal gland, the descending colon is medially reflected exposing the left kidney and renal hilum. Division of the splenorenal ligament and lateral peritoneal attachments will allow the spleen to fall away. The tail of the pancreas must be identified anterior and medial to the kidney and adrenal gland. The plane between the tail of the pancreas and the left adrenal gland is developed by separating Gerota's fascia from the mesentery of the descending colon. Careful dissection of the left renal vein will allow identification of the adrenal vein coursing into its superior aspect opposite the gonadal vein. Working backwards, the adrenal vein leaves the left renal vein, joins with the inferior phrenic vein and courses anterior to the adrenal gland to enter its hilum. Ligation of the left adrenal vein followed by medial traction will allow dissection between the left kidney and the adrenal gland.

The right adrenal gland when approach transperitoneally begins with the medial mobilization of the ascending colon followed by Kocherization of the duodenum to expose the inferior vena cava. The right adrenal vein is a short vein that can be found superior to the right renal vein entering the vena cava posterolaterally. Sometimes an accessory vein can be found as it enters

the inferior phrenic vein. Surgical control of this vein is very important since injury to the vein can cause profuse blood loss. The arterial blood supply as described above forms a plexus that can be controlled with surgical clips or vascular sealing devices (Ligasure®, Harmonic Scalpel®).

3. KIDNEYS

3.1. *General Considerations*

The kidneys are located in the retroperitoneum and can therefore be approached via retroperitoneoscopy or transabdominal laparoscopy. At the present time, the transabdominal approach to most surgical entities is favored and is the better approach to robotically-assisted surgery in children and will therefore be the approach discussed in this book.

Each kidney is enclosed superiorly, medially, and laterally by Gerota's fascia. This renal fascia is made up of a flimsy anterior layer that is closely associated to the peritoneum and a distinct tougher posterior layer. These anterior and posterior layers of renal fascia separate the retroperitoneal space into three potential spaces: the anterior pararenal compartment contains the ascending colon and duodenum on the right side and the descending colon and pancreas on the left side; the intermediate pararenal compartment contains the adrenal glands, kidneys, perirenal fat, and the proximal ureter; the posterior pararenal compartment consists of adipose tissue. The anterior space is different from the posterior and intermediate compartment as it extends from one side of the abdominal cavity to the other. The pararenal fat, a separate layer of adipose tissue, surrounds Gerota's fascia both anteriorly and posteriorly.

The kidneys can each be related to its topographic neighbors; some are common to the two kidneys and others are lateralized. The lower two-thirds of each kidney lay on the psoas medially. Laterally, the kidneys encounter the quadratus lumborum and the aponeurosis of the transversus abdominis muscle.

Right kidney: The right kidney is lower than the left kidney and is crossed by the 12th rib. The upper pole lies adjacent to the liver superiorly and the peritoneum separates the two. The posterior portion of the liver is connected to the superior pole of the right kidney by an extension of parietal peritoneum referred to as the hepatorenal ligament. The descending portion of the duodenum lies anterior to the vena cava and renal vein and lies very close to the medial aspect of the kidney and renal hilum.

Left kidney: The left kidney lies slightly higher than the right and is crossed by both the 11th and 12th ribs. The upper pole lies adjacent to the spleen. The splenic flexure and descending colon lay anterolaterally to the left kidney. Superiorly the left kidney is bordered by the tail of the pancreas. The splenic artery and vein lie adjacent to the upper pole of the kidney and hilum.

3.2. Kidney Exposure

Right kidney: Transabdominal laparoscopic robotic surgery upon on the right kidney is performed with the patient in the 45 degree left lateral decubitus position. In this position, the right kidney is seen lying behind the right colon and its mesentery. The right colon must be mobilized medially in order to expose the kidney and Gerota's fascia. To accomplish this mobilization, the colon will be freed from its attachment to the abdominal wall, the white line of Toldt. This distinct layer can be distinguished from Gerota's fascia by looking for the line of capillaries coursing from the abdominal wall to the colon's lateral edge. Once the line of Toldt is divided and the colon reflected medially, the peri-renal fascia is exposed. Following colonic mobilization, the duodenum is encountered on the right side. The duodenum can be confused with the inferior vena cava; however the inferior vena cava always lies posterior to the duodenum. Sharp dissection of the lateral attachments of the duodenum will facilitate Kocherization of the duodenum medially exposing the vena cava and right renal vein. Inferior to the lower pole of the right kidney, the gonadal vein can be identified medial to the ureter. The gonadal vein courses cephalad and enters the lateral portion of the inferior vena cava just inferior to the renal hilum.

Left kidney: Similar to the right side, when approaching the left kidney, the patient also lies in the 45 degree right lateral decubitus position. The small bowel falls medially, secondary to gravity, and exposes Gerota's fascia encompassing the left kidney which appears inferior to the descending colon and its mesentery. The colon is mobilized medially, again, by dividing the white line of Toldt. In the left upper quadrant lies an avascular adhesion which connects the spleen and the upper pole of the kidney to the lateral abdominal wall and diaphragm. It is important to divide this structure to facilitate separation of the spleen from Gerota's fascia. The splenocolic ligament attaches the superior and anterior portion of Gerota's fascia to the spleen. Release of this attachment facilitates the medial mobilization of the descending colon. The tail of the pancreas, with its pale lobulated appearance, usually falls medially with the release of the splenocolic ligament and mobilization of the descending colon. In some instances, the tail of the pancreas can remain attached to the perirenal fascia. Identification of the characteristic appearance of the pancreas will allow the surgeon to safely mobilize it away from the operative field. Inferior to the lower pole of the left kidney, the gonadal vein can be identified medial to the ureter. On the left side, the gonadal vein runs medial to the ureter and enters into the inferior aspect of the left renal vein.

Renal mobilization and exposure allows for performing all robotically assisted surgeries on the kidneys of children. Knowledge of the anatomical landmarks and the movement of organs that cover the kidneys in the anterior to posterior direction allows for renal exposure. Such surgeries as cyst decortication and pyeloplasty can be performed with the limited

exposure discussed. However, other surgeries such as nephrectomy or hem-inephroureterectomy require a thorough knowledge of the renal vasculature located in the hilum.

3.3. Renal Hilum Anatomy and Dissection

The renal hilum consists of the renal pedicle, renal pelvis and ureter. During surgical dissection, identification of the gonadal vein on either side following them cephalad will allow identification of the renal hilum of interest. Classically single renal arteries bilaterally branch off of the aorta at the level of the second lumbar vertebra, inferior to the take-off of the superior mesenteric artery. The right renal artery exits the aorta and courses caudally under the IVC heading toward the right kidney. The left renal artery exits the aorta in a direct lateral course toward the left kidney. Both renal arteries take a posterior course and give off branches to the ureter, renal pelvis, and adrenal gland prior to entering the kidney. The renal artery branches into five segmental arteries which each supply a specific portion of the kidney as end arteries. The first branch, most commonly, is the posterior segmental artery which branches prior to the hilum. Classically, the four anterior branches are apical, superior, middle, and inferior from top to bottom. During heminephrectomy it is important to understand the relationship of these segmental branches. The anterior segmental arteries run above the renal pelvis while the posterior segmental artery courses underneath the renal pelvis. The renal vein courses anterior and superior to the renal arteries. The right renal vein is typically short, non-branching and enters the inferior vena cava. The left renal vein is longer and accepts the gonadal vein at its inferior aspect and the left adrenal vein adjacent to the gonadal vein at its superior aspect. The order of the structures in the renal hilum from anterior to posterior are the renal vein, renal artery, followed by the renal pelvis.

3.4. Renal Anomalies

3.4.1. Crossing Vessels

It is unclear whether a crossing blood vessels cause ureteral obstruction or merely co-exists along with a narrowed ureteral segment. When a lower pole renal artery crosses over the ureter, Stephens postulated that the angulation of the ureter at the UPJ during filling of the pelvis can obstruct the ureter at the UPJ and at the point where the vessel crosses over the ureter (4). This process may worsen as an inflammation develops and the ureter can become adherent to the UPJ.

3.4.2. Duplication Anomalies

One in 125 people are born with complete duplication of the collecting system (5) where there are separate ureters each entering into the bladder or

an ectopic insertion. In some cases, removal of one moiety with/without its attendant ureter is indicated. Upper pole heminephrectomy or heminephroureterectomy may be indicated in cases of poor function or dysplasia secondary to an ectopic insertion of the ureter or ureterocele (more commonly in girls). Lower pole surgery may require reconstruction in the form of pyeloplasty in the presence of a ureteropelvic junction obstruction. Otherwise heminephrectomy for dysplasia or non-function from long-standing severe obstruction or high grade vesicoureteral reflux). In cases of heminephrectomy, the poorly functioning renal unit along with its ureter is removed. During dissection near the lower pole of the kidney or after bowel mobilization, the dilated tortuous upper or lower pole ureter can usually be identified. The ureter draining the normal system runs parallel and adjacent to the dilated segment and can be identified by its peristaltic waves. The main renal artery and vein should be identified and mobilized as they cross over the upper pole collecting system. The segmental branches supplying the upper and lower pole moieties can then be identified.

3.4.3. HORSESHOE KIDNEY

The most common renal fusion anomaly is the horseshoe kidney. The incidence of horseshoe kidney has been reported to occur in 1 in 400–1800 individuals *(6)*. In greater than 90% of cases the lower poles are connected by the isthmus which crosses the midline. The isthmus usually lies inferior to the inferior mesenteric artery since it is believed that the inferior mesenteric artery prevents the ascent of the fused renal units. The kidneys are malrotated anteriorly due to fusion of the kidneys prior to the completion of the medial rotation during development. The calyces are usually oriented anteroposterior. The most inferior calyces commonly lie over the vertebral column and face the midline, medial to the ureter. The upper poles lie farther apart than the lower poles with a vertical orientation of the renal axis. Although variable, the ureters typically run anterior to the pelvis. Thirty percent of patients with a horseshoe kidney will be diagnosed with a UPJ obstruction due to a high ureteral insertion or a crossing segmental vessel *(7)*. It is important to differentiate a true obstruction from calyces that appear obstructed due to malrotation. The blood supply to the horseshoe kidney is variable originating from the lower aorta, common iliac arteries, and internal iliac arteries.

3.4.4. URETEROPELVIC JUNCTION OBSTRUCTION

Ureteropelvic junction (UPJ) obstruction is common in children and is currently most commonly suspected in utero and confirmed post-natally. Robotically assisted laparoscopic surgery is undertaken either to correct the obstruction or to remove the kidney. The surgical principles for robotic pyeloplasty are the same as for open repair and involve identification and exposure of the ureteropelvic junction as described above, dissection of an

ample segment of ureter without injuring the blood supply (see below) and then reconstruction. Nephrectomy requires isolation, ligation, and division of the renal vasculature and its ligation, ureteral division, and division of the ligamentus and adventitial bindings of the kidney. While younger children are typically affected by a dysplastic segment of ureter, older children may have an obstruction when the UPJ and proximal ureter become kinked under the overlying posterior segmental arterial branch. It is imperative to identify and preserve the arterial crossing vessel since it provides blood supply to the lower pole of the kidney and possibly even the upper ureter. Any venous branches seen coursing along side arterial branches or alone may be divided. The ureteral narrowing can be corrected with excision of any abnormal segment and transposition of the UPJ to the other side of the crossing vessel followed by ureteropyeloplasty.

4. URETERS

The ureters lie posterior to the renal vessels and start at the ureteropelvic junction. When the ureters are approached at the level of the kidney, they become exposed once the colon is mobilized and the psoas major muscle is exposed. The ureter is encountered by following the medial edge of the psoas muscle starting at the lower pole of the kidney. When they are encountered near the kidney, the ureters can be traced cranially up to the ureteropelvic junction. The ureters course along the anterior border of the psoas as it begins its descent toward the bladder. The right ureter runs in proximity to the ascending colon and its mesentery. The left ureter has a close association with the descending colon and its mesentery. The gonadal veins run along side both ureters. The left gonadal vein enters into the left renal vein and the right gonadal vein empties directly into the inferior vena cava. The ureters can be distinguished from the gonadal veins by noting the characteristic peristalsis and also by its location posterior and lateral to the gonadal veins. The gonadal vessels cross the ureters anteriorly at about one-third of the way to the bladder. At the bifurcation of the common iliac and the internal and external iliac arteries the ureter crosses anterior to enter the pelvis. In the male, the lower third of the ureter courses under the vas deferens at the level of the seminal vesicle. In females, the ureter runs posteriorly through the ovarian fossa and travels lateral to the cervix going underneath the broad ligament. Prior to entering the bladder, the ureter runs under the uterine artery (water under the bridge). Thus the ureter can be segmented into three parts: upper third (from the renal pelvis to the top of the sacrum), middle third (length of the sacrum), and lower third (from the bottom of the sacrum to the bladder).

The blood supply to the ureter is derived from multiple sources along its path. The renal artery, abdominal aorta, gonadal artery, and common iliac artery all supply arterial branches to the upper portion of the ureter. It is important to note that these upper branches all enter the uretermedially.

In the female, the vesical, uterine, and middle rectal and vaginal arteries all branches of the internal iliac artery supply small arterial branches to the distal ureter. In the male, the distal ureter is supplied from branches of the aorta, gonadal artery, common and internal iliac arteries. These distal branches enter the ureter laterally which differs from the arterial supply in the upper ureter. Once the arterial vessels reach the ureter they anastomose in a plexus that runs longitudinally within the adventitia of the ureter. The venous drainage of the ureter runs parallel to its arterial supply.

The circumcaval or retrocaval ureter presents on the right side with ureteral obstruction. Thus anomaly represents aberrant development of the embryonic inferior vena cava in which the posterior cardinal vein fails to involute and its persistence places the ureter posterior to the vena cava at the level of the 4th lumbar vertebrae redirecting the ureter toward a medial course. The right ureter courses medial after leaving the UPJ and runs underneath the vena cava until it deviates laterally to enter the bladder. The kinked ureter is commonly reconstructed when this anomaly causes flank pain, recurrent urinary infections, or obstruction.

5. RETROPERITONEAL LYMPHATICS

The five main retroperitoneal lymph node chains all derive their names from their anatomic relationship to the aorta and vena cava. The right paracaval nodes begin inferior to the right renal vein and extend caudally to before the bifurcation of the common iliac veins. The lateral border is the right ureter and the medial border is the vena cava. The pre-caval nodal chain courses anterior to the inferior vena cava from the renal vein to the bifurcation. The interaortocaval nodes lie between the aorta and vena cava. Anterior to the aorta, lie the pre-aortic lymph nodes and the para-aortic lymph node chain extending from the left ureter to the border of the lateral border of the aorta. Both lymph node chains course cranially from the left renal vein to the common iliac artery.

Donahue et al. *(8)* described the lymphatic drainage pattern of the testicles. The right testicle drains first into the interaortocaval nodes and then to the pre-caval and preaortic nodes. The left testicle primarily drains into the pre-aortic and para-aortic lymph node chains and then into the interaortocaval nodes. Cross-over spread occurs more commonly with right-sided testicular tumors and thus the borders of lymph node dissection for right sided tumors take this fact into consideration. The modified template retroperitoneal lymph node dissection was developed to help to preserve antegrade ejaculation which requires an intact paravertebral sympathetic ganglia, and post-ganglionic sympathetic nerves from T2-L4 which coalesce at the hypogastric plexus *(9)*.

6. BLADDER

6.1. General Considerations

The urinary bladder can be visualized in every laparoscopic and robotic procedure of the lower urinary tract. Knowledge of its anatomy, blood supply, lymphatic drainage and anatomic relationships allows the urologic surgeon to safely navigate the pelvis. The capacity of the adult bladder is approximately 500 mL, whereas the capacity of the bladder in a child changes with age according to the formula: Volume (mL) = 30(age in years +2) *(10)*. When empty, the bladder forms a tetrahedron whose apex is at the urachus, 2 lateral surfaces and a posterior base which all lies inferiorly and anchor to the bladder neck. The urachus attaches the bladder to the abdominal wall anteriorly. The longitudinal smooth muscle of the urachus fans out at its insertion into the bladder and can be a source for bladder diverticula.

The obliterated umbilical arteries form the medial umbilical ligaments and run parallel to the urachus to enter the umbilicus alongside the urachus. When viewed laparoscopically, the bladder is seen in the midline with the medial umbilical ligaments identified on either side of the bladder (Fig. 1). Four different anomalies can occur at the urachus and can be surgically approached laparoscopically: patent urachus, umbilical-urachal sinus, urachal cyst, and a vesicourachal diverticulum. The urachus has an epithelial-lined lumen which may or may not remain patent and can develop adenocarcinoma.

In infants, the bladder lies more intra-abdominally with the bladder neck lying level with the upper border of the pubic symphysis. As the infant grows and reaches puberty, the bladder makes its way to reside in the true pelvis. The bladder is a retroperitoneal organ that resides under the pubic symphysis when empty and rises above the pubic ramus along the anterior abdominal wall as it fills. The peritoneum covers the dome of the bladder and courses posteriorly to the seminal vesicles to join the peritoneum overlying
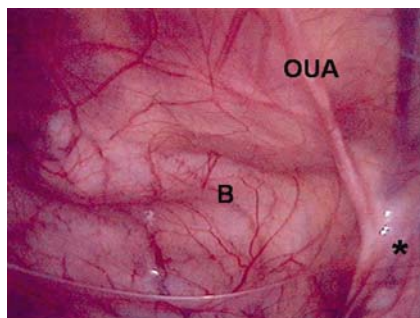
Fig. 1. Laparoscopic view of the pelvis. The bladder is located in the center of the field *(B)* flanked ob the right by the obliterated umbilical arteries *(OUA)*. Lateral to the OUA would be the internal inguinal ring (∗).

the rectum. In the male, the seminal vesicles lie on the posterior surface of the bladder and join the ampullae of the vas deferens bilaterally in the midline as they enter the prostate at the ejaculatory ducts. The prostate attaches to the bladder at the bladder neck. The ureters cross over the vas deferens bilaterally as they enter the bladder at the trigone.

In the female, the vagina and uterus lie anterior to the rectum and posterior to the bladder. The vesicouterine pouch is formed by the peritoneal reflection over the dome of the bladder as it courses over the uterus. The rectouterine pouch is formed as the peritoneum runs posteriorly over the uterus toward the anterior rectum.

The distal ureter enters the bladder at the trigone. As it approaches the bladder, it becomes enveloped by Waldeyer's fibromuscular sheath which parallels the distal ureter. The ureter enters the bladder at an angle and travels between the detrusor muscle and the bladder mucosa for a distance of 1.5–2 cm before terminating at the ureteral orifice. This submucosal tunnel creates a one-way valve which allows urine to enter the bladder. As the bladder fills, the pressure on the distal ureter within the submucosal tunnel likely prevents the backflow of urine into the ureter. When the ratio of the ureteral width to length of the submucosal tunnel is not sufficient, vesicoureteral reflux may occur. The robotic extravesical ureteral reimplantation uses an extravesical Lich-Gregoir technique of laparoscopic ureteral reimplantation *(11)*. In girls, the surgeon identifies the ureter cephalad to the uterus. Incision of the peritoneum anterior to the uterus with downward mobilization of the uterine ligament and pedicle aids in ureter identification. In boys, the ureter can be identified by following the vas deferens as it courses posterior to the ureter.

6.2. Blood and Lymphatic Supply

The urinary bladder receives its blood supply via branches of the internal iliac artery (Table 2). After crossing the sacroiliac joint the internal iliac artery splits into an anterior and a posterior division. The posterior division divides into three branches, the superior gluteal, the iliolumbar, and the lateral sacral artery. The anterior division divides into seven branches. The first branch is the obliterated umbilical artery which gives off the superior vesical artery proximally. The seminal vesicles and the vas deferens receive the vesiculodeferential artery, a branch of the superior vesical artery. The inferior vesical artery provides blood supply to the base of the bladder, distal third of the ureter, the prostate and seminal vesicles in the male and the vaginal in the female. In addition to the vesical branches, the bladder can receive blood flow from any of the following branches arising from the internal iliac artery. The obturator artery leaves the internal iliac and courses inferior and medial to the obturator nerve as it enters the obturator foramen to supply the thigh adductor muscles. The middle rectal artery provides some branches to the prostate and seminal vesicles and joins the superior

Table 2
Branches of the Internal Iliac Artery

Division	Branch	Sub-branches	Destination
Posterior	Iliolumbar artery	Lumbar and iliac branches	Psoas major muscle, quadratus lumborum muscle, iliacus muscle
Posterior	Lateral sacral arteries	Superior and inferior branches	Anterior sacral foramina
Posterior	Superior gluteal artery	–	Greater sciatic foramen
Anterior	Obturator artery (occasionally from inferior epigastric artery)	–	Pelvis – branches to the iliacus and bladder
Anterior	Inferior gluteal artery	–	Greater sciatic foramen
Anterior	Umbilical artery	superior vesical artery	Medial umbilical ligament
Anterior	Uterine artery (females) or deferential artery (males)	superior and vaginal branches	Uterus, vas deferens
Anterior	Vaginal artery (females, can also arise from uterine artery) or inferior vesical artery (males)	–	Vagina, urinary bladder
Anterior	Middle rectal artery	–	Rectum
Anterior	Internal pudendal artery	Terminal branch of the anterior trunk	Supplies branches to penis, clitoris, labia, scrotum and perineum
Anterior	Inferior gluteal artery	–	Greater sciatic foramen
Anterior	Umbilical artery	superior vesical artery	Medial umbilical ligament
Anterior	Uterine artery (females) or deferential artery (males)	superior and vaginal branches	Uterus, vas deferens

Table 2 (Continued)
Branches of the Internal Iliac Artery

Division	Branch	Sub-branches	Destination
Anterior	Vaginal artery (females, can also arise from uterine artery) or inferior vesical artery (males)	–	Vagina, urinary bladder
Anterior	Middle rectal artery	–	Rectum
Anterior	Internal pudendal artery	Terminal branch of the anterior trunk	Supplies branches to penis, clitoris, labia, scrotum and perineum

rectal artery (a branch of the inferior mesenteric artery and inferior rectal arteries (a branch of the internal pudendal artery). The uterine artery travels along the lateral wall of the uterus to join the ovarian artery near the fallopian tube. It crosses over and cephalad to the ureter giving rise to the expression ("water flows under the bridge). Understanding this relationship can help the robotic surgeon avoid injuring the ureter when dividing the uterine pedicles. The inferior gluteal and the internal pudendal arteries can also contribute branches to the bladder. The blood supply to the bladder can also be referred to as the posterior pedicle running in the posterior vesical ligament in the male and the uterosacral ligament in the female. It can be found posterior and medial to the ureter. The lateral pedicles course lateral to the ureters and course in the vesical ligament in the male and the cardinal ligament in the female. The veins of the bladder follow the course of the arteries and coalesce into the vesicle plexus and drain into the internal iliac vein.

The lamina propria and muscularis provide lymphatic drainage which course alongside the superficial vesicle vessels passing small paravesical lymph nodes in its course to drain in the external iliac lymph nodes (the main lymphatic drainage side of the bladder). Accessory lymphatic drainage occurs anteriorly and laterally through the internal iliac and obturator nodes. The common and internal iliac chain can also receive lymphatic drainage from the bladder base and trigone.

7. BOWEL ANATOMY AND BLOOD SUPPLY IMAGE

The pediatric urologic surgeon needs to have a thorough understanding of intestinal anatomy and vasculature. The most frequently used gastrointestinal segments that are used for bladder reconstruction are the ileum,

the appendix, and the sigmoid colon while MACE procedure is commonly performed using sigmoid or cecum. Understanding the anatomy of the bowel segments and their blood supply (Table 3) is very important prior to approaching these reconstructive procedures.

Table 3
Branches of the Abdominal Aorta

Artery	Location	Take off	Destination
Celiac Trunk	Anterior	Immediately inferior to aortic hiatus of the diaphragm	Stomach, spleen, liver, pancreas, duodenum
Inferior Phrenic Arteries	Lateral	Immediately inferior to aortic hiatus	Diaphragm
Superior Mesenteric Artery	Anterior	Immediately inferior to celiac trunk	Pancreas, duodenum, jejunum, ileum, ascending and transverse colon
Middle Adrenal Arteries	Lateral	Immediately superior to renal arteries	Adrenal glands
Renal Arteries	Lateral	Immediately inferior to superior mesenteric artery	Kidneys
Inferior Mesenteric Artery	Anterior	Inferior to renal arteries	Descending colon, sigmoid, rectum
Testicular or Ovarian Arteries	Anterolateral	Inferior to renal arteries	Testes in male and ovaries in female
Lumbar Arteries	Posterior	Usually four pairs between the renal arteries and the common iliac arteries	Posterior abdominal wall and spinal cord
Median Sacral Arteries	Posterior	Just cephalad to aortic bifurcation	Rectum, sacrum, coccyx
Common Iliac Arteries	Split	Aorta usually bifurcates at the L4 vertebral body	Pelvis and lower extremities

7.1. Small Intestine

The small intestine ranges from 15 to 30 feet in the adult and changes with age in children. The small intestine begins distal to the stomach with the duodenum. Distal to the duodenum the jejunum comprises about 40% of the small bowel. The ileum is the most distal portion of the small intestine. Intraoperatively the ileum can be differentiated from the jejunum due to its smaller caliber, thicker mesentery with smaller vessels in its multiple arcades and its distal location as it enters the cecum. The superior mesenteric artery provides the blood supply to the small intestine through multiple arcades which then send direct vertical branches to the bowel wall. During isolation of a bowel segment it is important to find a substantially palpable artery feeding the segment. It is also imperative not to clear the mesentery further than 8 cm away from the vertical feeding vessel to prevent bowel necrosis.

7.2. Large Intestine

The large intestine consists of the cecum, ascending colon, transverse colon, descending colon, sigmoid colon, and rectum. Some of the large intestine lies in the retroperitoneal space while other portions reside freely in the peritoneum. Although the cecum can be freely mobile, it most commonly resides in the right lower quadrant fixed to the posterior lateral abdominal wall and retroperitoneum by peritoneal attachments. The ascending colon has an attachment to the liver via the hepatocolic ligament (hepatic flexure) and is secured to the right posterior abdominal wall within the peritoneum. The transverse colon is attached at the spleen and stomach by the phreno-colic ligament and gastrocolic omentum and moves freely between the liver and spleen. The descending colon like the ascending colon is fixed to the abdominal wall laterally. The sigmoid colon begins as an intraperitoneal structure and enters the retroperitoneum as it courses caudally.

The appendix is located at the base of the cecum and can be anywhere from 0.5 to 9 in. in length. Its location can vary from subcecal, retroileal to retrocolic. It has a variable mesentery with the appendicular artery usually coming from the posterior cecal artery.

The blood supply of the large intestine consists of branches from the superior and inferior mesenteric arteries as well as the internal iliac arteries. The arteries all anastomose to one another and form the marginal artery of Drummond. The right colic and middle colic arteries branch off of the superior mesenteric artery to provide blood supply to the ascending colon and the right half of the transverse colon, respectively. The terminal branch of the superior mesenteric artery is the ileocolic artery which provides blood supply to the distal ileum and proximal ascending colon. The inferior mesenteric artery first branches as the left colic artery which supplies the descending colon. The inferior mesenteric artery then gives off multiple sigmoid branches and terminates in the superior hemorrhoidal artery. The internal iliac artery provides the middle hemorrhoidal artery and the internal

pudendal artery terminates as the inferior hemorrhoidal artery. The three vessels all anastomose and provide collateral flow to the colon and rectum.

8. INTERNAL RING AND THE INGUINAL CANAL

The testicle has three sources of blood supply that are identified laparo-scopically. The main blood supply to the testicle is provided by the testicular artery which branches from the aorta below the renal vessels and courses adjacent to the gonadal vein to enter the inguinal canal. The deferential artery, a branch of the superior vesical artery, travels along side the vas deferens and provides a secondary arterial blood supply to the testicle. The third arterial blood source, the cremasteric artery, comes from the inferior epigastric artery. The veins of the pampiniform plexus provide the testicle's venous drainage and coalesce to form the gonadal vein. As previously mentioned, the right gonadal vein drains directly into the inferior vena cava while the left gonadal vein drains into the left renal vein.

The inguinal canal provides passage of the spermatic cord in the male and the round ligament in the female. The ilioinguinal nerve courses through the inguinal canal in both men and women. The aponeurosis of the external oblique muscle forms the roof and then condenses at its inferior edge to become the inguinal ligament. As the external oblique aponeurosis approaches the pubic tubercle, its fibers split to form the external inguinal ring. The transversalis fascia, which lines the inner surface of the abdominal wall, comprises the floor of the inguinal canal. The internal inguinal ring starts out almost adjacent to the external ring during infancy but will become superior to the inguinal ligament and 4 cm lateral to the external ring in the late adolescent/adult patient. The spermatic cord leaves the inguinal canal through the internal inguinal ring lateral to the inferior epigastric vessels. The conjoined tendon consists of fibers of the internal oblique and transversus abdominis muscles which coalesce lateral to the internal ring and cover the inguinal canal underneath the external oblique aponeurosis. Hernias of the inguinal canal may occur medial (direct) or lateral (indirect) to the inferior epigastric vessels.

There are clinically significant anatomical considerations at the level of the internal inguinal ring. Inspection of the normal internal inguinal ring will identify a closed ting without any patency of the peritoneum into the entrance of inguinal canal. The blood supply and return to the testis as well as its lymphatic drainage will be seen entering the internal ring laterally as the vas enters it medially (Fig. 2).

8.1. Conditions Related to the Internal Inguinal Ring

8.1.1. CRYPTORCHIDISM

Cryptorchidism, failure of complete testicular descent, occurs in 0.8–1.8% of full-term boys. *(12)*. The testicle fails to descend completely
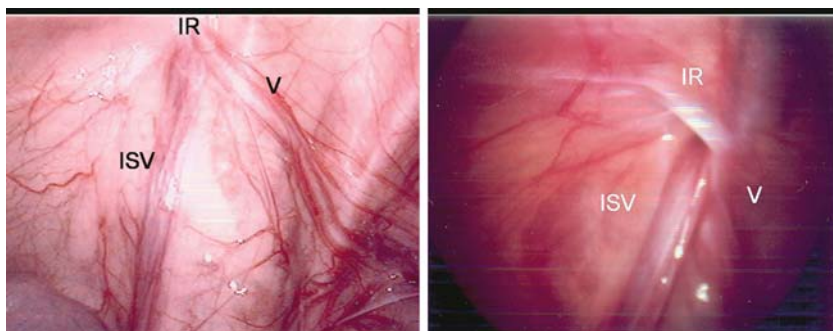
Fig. 2. Laparoscopic views of the pelvis in the area of the internal inguinal ring *(IR)*. The ring represents the entrance to the inguinal canal; the point where the internal spermatic vessels *(ISV)*, located laterally, and the vas, coming from the medial aspect, come together and travel toward the testis. The difference between the two images is that the IR on the left side is closed while the one on the right is open and may represent a clinical inguinal hernia.

to its normal position in the scrotum by 1 year thus requiring surgical intervention. In 80% of males with an undescended testicle, the gonad is palpable somewhere in the inguinal canal or upper scrotum. Inability to palpate the testicle in the remaining 20% can be due to an testicular agenesis, intraabdominal location, location somewhere along the inguinal canal or presence in an ectopic location.

In the laparoscopic approach to the non-palpable testicle, the peritoneal cavity is entered via a supraumbilical or infraumbilical incision after empting the bladder to avoid injury from the trocar placement. After entering the peritoneum the normal anatomic landmarks should be identified as described above (Fig. 3). Thebladder can be seen in the center of the operative field behind the peritoneum and between the paired median umbilical ligaments. The vas deferens bilaterally can be seen in the midline after
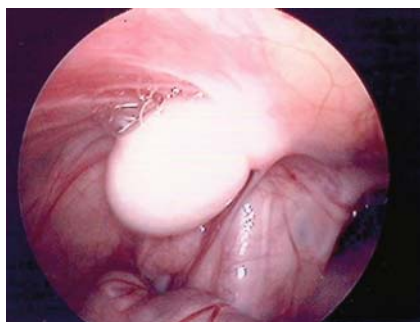
Fig. 3. Laparoscopic view of an intrabdominal testis sitting at the verge of an open internal inguinal ring.

exiting the prostate and coursing laterally, crossing the median umbilical ligaments toward the corresponding internal ring. The internal inguinal ring can be identified by following the spermatic vessels coursing down the lateral abdominal wall and its convergence with vas deferens on the non-affected side. Inspection of the internal ring on the affected side will show one of the following scenarios:

1. The inguinal ring may be closed with a normal vas deferens and spermatic vessels entering the ring. Groin exploration in this case may reveal a testicular nubbin. Removal of the nubbin is controversial since 10–15% of testicular nubbins can have viable testicular tissue and could theoretically undergo malignant transformation *(13)*.
2. An open inguinal ring may be seen with normal appearance of the testicular vessels and vas deferens. In many cases the testicle will be seen within 1 cm of the ring. If the testicle is peeping into the open ring, it can be pushed into the abdomen by massaging the canal.
3. The ring is closed and the testicular vessels are seen coursing up the lateral abdominal wall and blindly ending in a "horse-tail" appearance. When this occurs a blind ending vas deferens is usually seen closely associated to the blind ending vessels. This is diagnostic of agenesis of the testicle or a vanishing testicle. A vanishing testicle can only be confirmed by finding blind ending vessels and not just a closed ring or atretic vas deferens
4. An intraabdominal testicle is identified attached to normal vessels and vas with an open ring.
5. Gonadal disjunction occurs when a blind ending vas deferens is identified without testicular vessels being readily identified. In this instance, it is imperative to follow the normal course of the testicular vessels cephalad toward the aortic origin until the testicle can be found.

While the scrotum is not an intrabdominal structure, it is an important anatomic structure for laparoscopic orchidopexy. Scrotal skin is composed of both sebaceous and sweat glands, hair follicles and pigmentation. It does not have any adipose tissue and depending on its underlying muscle tone will hang loosely or will contract with horizontal rugae. The fusion of the genital tubercles forms the midline raphe which runs from the tip of the glans penis to the anus. During testicular descent through the inguinal canal, the testicle invaginates the various layers of the abdominal wall and forms the various spermatic fascias that make up the layers of the scrotal wall. The fascia of the external oblique forms the external inguinal ring and becomes the external spermatic fascia. The internal oblique muscle and fascia become the cremasteric muscle and fascia. The transversalis fascia continues into the scrotum as the internal spermatic fascia. The tunica vaginalis consists of parietal and visceral layers which surround the tunica albuginea of the testicle and has its derivation from the peritoneum. In utero, the tunica vaginalis communicates with the peritoneal cavity via a patent processus vaginalis. The gubernaculum fixes the testicle to the scrotum via the lower pole.

8.1.2. VARICOCELE

A varicocele can be detected by palpation in almost 15% of teenage boys. In most cases, varicoceles are asymptomatic and are detected at routine physical examinations. It may lead to growth arrest and histologic abnormalities of the testis resulting in reduced fertility. In teenagers, varicoceles usually produce no symptoms and they are usually detected on routine physical examination. It is believed that varicoceles develop due to pooling of blood in the pampiniform plexus due to incompetence of the venous valves within the gonadal vein causing increased resistance as it drains into the left renal vein *(14)*. Several approaches have been described to treat varicoceles including surgical and radiological techniques. The surgical techniques to approach varicoceles include retroperitoneal, inguinal, subinguinal, and laparoscopic procedures *(15–17)*. The anatomy encountered during the laparoscopic approach to a left varicocele is described below. Once pneumoperitoneum is established, three ports are placed into the peritoneal cavity. Identification of the left internal inguinal ring will allow the surgeon to identify the spermatic artery and veins coursing from the ring retroperitoneally in a cephalad direction toward the left renal vein. The vas deferens will be seen exiting the inguinal ring lateral to the inferior epigastric vessels and coursing medially along the pelvic side wall, anterior to the median umbilical ligament to enter the base of the prostate posteriorly. Once the dilated spermatic vessels are identified coursing into the inguinal ring, an incision is made in the posterior peritoneum lateral to the vessels proximal to the internal inguinal ring. Blunt mobilization of the entire spermatic artery and veins can be accomplished through this peritoneal window (Fig. 4). The vessels can then be divided with surgical clips.

Fig. 4. Laparoscopic view of the internal spermatic vessels elevated by an instrument in anticipation of its clipping and division as part of a laparoscopic varicocelectomy.

9. CONCLUSION

A thorough appreciation of anatomy is very important for the surgeon performing robotically assisted laparoscopic surgery. As the scope of robotic

surgery continues to expand, a greater comprehension and understanding of the anatomic relationships will also expand. We hope this review has been helpful to further this appreciation.

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2 Physiology of Pediatric Genitourinary Laparoscopy

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Abstract The expanding scope of paediatric genitourinary laparoscopy has meant that increasingly complex procedures are being carried out in ever younger patient populations. Surgeons and anaesthetists alike have thereby been confronted with and gained awareness of a mounting repertoire of physiological consequences related to both intra and retroperitoneal gaseous insufflation. The physiological responses encountered clinically are mainly due to the mechanical and biochemical effects of carbon dioxide (CO_2) insufflation. CO_2 is absorbed across the thin peritoneal membrane of paediatric patients resulting in hypercarbia and acidosis and leads to an increased CO_2 load presented to the lungs. Mechanically, the increased intraabdominal pressure decreases lung compliance and worsens ventilation perfusion mismatch, ultimately leading to hypoxia. Cardiovascularly, the paediatric patient is prone to developing increases in systemic and pulmonary vascular resistance resulting in significant decreases in cardiac output. These cardiopulmonary effects are pressure dependent and have an occurrence that is inversely proportional to patient age and weight, warranting use of the lowest insufflation pressures possible, especially when dealing with very young and/or acutely ill patients.

Abdominal insufflation also leads to acute elevations in intracranial pressure, a caveat with specific relevance to genitourinary laparoscopy as myelodysplastic patients constitute a significant patient subgroup who stand to benefit from laparoscopic procedures under specific precautionary measures. Other physiological consequences include effects on renal function, thermoregulation, surgical stress and metabolism. Despite this long list of untoward physiological effects the overwhelming majority of genitourinary

laparoscopic procedures in paediatric patients are carried out safely as long as proper close monitoring, and required ventilatory adjustments are instituted.

Keywords Physiology · Insufflation · Laparoscopy · Robotics · Paediatrics

1. INTRODUCTION

Safe and successful laparoscopic surgery is dependent on the creation of sufficient working space in the abdominal cavity, to allow adequate visualization and enough room for manipulation of laparoscopic instruments. This is even more of an issue when it comes to laparoscopy in children and infants, let alone the neonates, who by the very nature of their tiny and compact anatomy rarely allow more than a few centimetres of vertical working space under the best of conditions *(1)*. To achieve these ends, various methods and contraptions have been employed of which creation of pneumoperitoneum (PnP) is by far the most prevalent *(2,3)*. PnP facilitates laparoscopy by expanding the abdominal cavity and suppressing the bowels and viscera thereby giving the laparoscopic surgeon overview and unhindered manoeuvrability. However for all its advantages, PnP brings with it a whole host of "if not unforeseen" then at least to some extent "often neglected" physiological ramifications which surgeons and anaesthetists have only slowly but steadily begun to identify and appreciate.

In paediatric urology, as in other specialities, where indications for laparoscopy have been expanding exponentially it is only natural that physiological aspects of minimally invasive surgery are receiving increasing attention. Especially as technological advances, miniaturization of instruments and the introduction of robotics have meant that increasingly complex procedures are being carried out in an ever younger patient population. Furthermore, genitourinary minimally invasive surgery, in light of its specifics, entails that some procedures can be performed via retroperitoneoscopic access which adds yet another dimension to the understanding of percutaneous endoscopic surgical physiology. The current chapter explores the physiology of genitourinary laparoscopy based on evidence acquired from a growing body of literature, and will try to present hitherto agreed upon facts in a clinical context and as they pertain to paediatric urology.

2. ABDOMINAL INSUFFLATION

In genitourinary minimally invasive surgery, access can be attained by either the transperitoneal or retroperitoneal route. Initial access in both instances is achieved by open cut down techniques *(4,5)* A trocar is subsequently introduced through which gas is insufflated at variable rates to achieve pressures that range between 6 and 15 mmHg. The ideal insufflant has yet to be identified, and in its absence carbon dioxide (CO_2) has been found to be the most suitable alternative. The "ideal" gas would have to have

limited absorption and no physiological effects when absorbed. Furthermore, it would have to have a high solubility in blood and be rapidly excreted if absorbed or inadvertently injected intravascularly so as to limit any possibility of air embolus formation. Last and in no way least such a gas should not be capable of supporting combustion. Air and oxygen have limited physiological systemic effects but cannot be considered as they support combustion. Helium, which is an inert gas, has minimal systemic effects; however, it is relatively insoluble thereby increasing the risks of air embolism and cardiovascular complications during laparoscopy *(6,7)*. It has however been used successfully in selected adult patients deemed unfit for CO_2 PnP due to severe cardiovascular compromise and inability of effective CO_2 clearing *(8)*. Other gases such as nitrous oxide, nitrogen and argon have also been evaluated but never achieved widespread use as their drawbacks exceed any potential advantage over CO_2 (Table 1) *(9)*. CO_2 is thus the gas of choice at the vast majority of laparoscopic centres; it is colourless, odourless and cheap, has a high solubility in blood and is readily excreted by the lungs once absorbed. CO_2 is however readily absorbed leading to hypercarbia and acidosis with the potential for attendant deleterious systemic effects.

Table 1
Different insufflants and their characteristics

Gas	Blood solubility	Systemic effects	Combustion	Comment
"Ideal gas"	High	None	Suppresses combustion	Ideal, no disadvantages fulfils all criteria. Non existent!
Carbon dioxide	High	Yes	Suppresses combustion	Substantial transperitoneal absorption leading to systemic side effects, and peritoneal irritation. However, low risk of gas emboli
Helium	Low	Minimal	Suppresses combustion	Risk of gas embolism
Nitrous oxide	Low	Minimal	Supports combustion under certain circumstances	Risk of gas embolism. May have analgesic effects

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Table 1
(Continued)
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Gas	Blood solubility	Systemic effects	Combustion	Comment
Atmospheric air	Low	Minimal	Supports combustion	Supports combustion, and there is substantial risk of air emboli
Nitrogen	Low	Minimal	Suppresses combustion	Risk of gas embolism
Argon	Low	Minimal	Suppresses combustion	Risk of gas embolism

3. PULMONARY RESPONSE

Intra and retroperitoneal CO_2 insufflation lead to abdominal distension and an increase in intraabdominal pressure (IAP). The diaphragm is pushed in a cephalad direction and its excursion is limited by the increased IAP. This leads to a decrease in total lung compliance, an increase in peak inspiratory pressure (PIP) and a decrease in functional residual capacity (FRC) relative to closing pressure. These changes further increase the ventilation perfusion mismatch which already is skewed by the effects of general anaesthesia and mechanical ventilation. Combined with the absorption of CO_2 occurring across the stretched peritoneum, this may lead to hypercarbia, acidosis and ultimately hypoxemia especially in neonates and infants who have a low FRC, high closing pressure and high oxygen consumption. Patient positioning in the head down Trendelenburg position, as is often required in genitourinary laparoscopy, may further aggravate matters.

CO_2 absorption from the intra or retroperitoneal spaces leads to an increased load of CO_2 to the lungs, with an increased elimination *(10–12)* and can lead to acid-base imbalances in the form of acidosis *(13–16)*. Studies in paediatric patients have consistently documented significant increases in end tidal CO_2 (ET CO_2) in response to CO_2 insufflation *(1,10,17–23)*. In a retrospective institutional review of neonatal laparoscopy, Kalfa et al. found that ET CO_2 increased with an average of 33% over basal value in the majority of their patients despite ventilatory adjustments. This was higher than what is generally observed in adults, and overall these changes warranted adjustment of ventilatory minute volume to counteract the effects of the building hypercarbia in 84% of their cases. Furthermore, they were able to correlate the rise in ET CO_2 to insufflation pressure and length of procedure. An IAP <6 mmHg and procedures of shorter duration were thus less likely to be associated with ET CO_2 spikes *(18)*. A similar correlation between insufflation pressure and ET CO_2 was reported by Bannister et al. who examined the effects of stepwise increase in insufflation pressure on

several cardiorespiratory parameters of infants less than 12 months old. On average ET CO_2 increased by 13% and 41% of the patients developed some degree of hypoxemia, rendering at least one ventilatory adjustment necessary in 95% of their patients to restore ET CO_2 to within 10% of baseline value. The cut-off IAP at which changes in ET CO_2 and other parameters occurred was 10 mmHg *(17)*.

ETCO$_2$ is clinically used as a surrogate measure for arterial CO_2 partial pressure (PaCO$_2$) and plays an important role in anaesthetic monitoring *(12)*. There is however some debate as to whether ET CO_2 accurately reflects PaCO$_2$ especially in ventilated children undergoing laparoscopic surgery where ET CO_2 may misestimate PaCO$_2$ in the setting of increasing alveolar dead space and worsening of ventilation–perfusion mismatch. It is therefore recommended that monitoring be supplemented by arterial blood gas analysis especially during longer laparoscopic procedures *(19)*. Based on non-invasive ET CO_2 monitoring however, it has been shown that a 30–40% increase in minute volume ventilation is needed in order to maintain ET CO_2 in children undergoing laparoscopy *(20)*. A more reliable method of assessing CO_2 absorbed is by metabolic monitoring whereby the total amount of CO_2 eliminated from the lungs is measured (VE CO_2). This total amount of eliminated CO_2 represents both the CO_2 produced by metabolism and that absorbed. Simultaneous measurement of oxygen consumption indicates how much of the change in pulmonary CO_2 is the result of pure absorption *(11)*. In adult patients undergoing therapeutic laparoscopy, metabolic monitoring showed a significant build up of CO_2 absorption which plateaued within 15–30 minutes after institution of PnP and that VE CO_2 returned to baseline within 10 minutes of exsufflation *(11,12)*. Contrary to these findings and using a similar method, McHoney and colleagues studied VE CO_2 in paediatric patients undergoing laparoscopy comparing them to an age matched group who had open surgery *(10)*. This study also revealed a significant increase in VE CO_2 in children undergoing laparoscopic surgery; however, no plateau was reached indicating a continuous absorption of CO_2 across the peritoneal membrane throughout the duration of the procedure. The authors speculated that this might be a reflection of a different handling of intraperitoneal CO_2 in children as compared to adults and may be related to the characteristics of the thin peritoneal membrane in younger age groups which may allow more CO_2 absorption and a longer time before steady state is achieved. Furthermore, they noted a significant inverse correlation between VE CO_2 and patient age and weight which again adds credence to the aforementioned premise. A similar inverse relationship between age and CO_2 absorption was reported by Hsing *(24)*. Comparisons between intra and retroperitoneal CO_2 absorption are inconclusive. In pigs no significant difference in absorption was noted while a canine study showed that intraperitoneal insufflation lead to a more pronounced rise in PaCO$_2$ *(25,26)*. Adult human studies indicate that significantly more CO_2 is absorbed during retroperitoneal insufflation and that this might be related to a continued dissection of the retroperitoneal space which increases the surface area in contact with CO_2.

Retroperitoneoscopy has also been associated with higher risks of developing surgical emphysema and pneumomediastinum *(11,12,27)*. In children no direct comparisons between the two insufflation routes have been published.

There is a time lag for ET CO_2 to return to normal after exsufflation of the peritoneal cavity. Studies have shown this time frame to vary between 5 and 10 minutes depending on patient age and the accumulated amount of CO_2 and its effective washout by ventilatory adjustment performed during surgery *(23,24)*. In 35% of their patients McHoney et al. recorded an actual brisk rise in VE CO_2 upon exsufflation which peaked at about 6 minutes post exsufflation and lasted for an average of 17 minutes. This unexpected phenomenon was attributed to the systemic redistribution of CO_2-rich blood after relief of the tamponade effect of PnP on the venous return from the lower limbs, or the sudden increase in minute ventilation as IAP rapidly normalized upon exsufflation *(10)*. This time lag in normalization of both ET CO_2 and VE CO_2 is a sign of a persistent CO_2-burden post exsufflation, which is handled by respiratory excretion. Clinically, this warrants continued close monitoring of especially younger children in the immediate postoperative period.

Mechanical effects of PnP and patient positioning have also been examined and have been found to contribute significantly to any respiratory impairment observed. The infant is a diaphragmatic breather and hence the cephalad diaphragmatic shift caused by increased IAP and the Trendelenburg position impairs the infant's respiratory capabilities and renders them dependant on mechanical ventilation. In its self, the Trendelenburg position decreased lung compliance by 17%, and increased PIP by 19%. Addition of 12 mmHg PnP further decreased compliance by 27% compared to baseline and increased PIP by 32% of baseline value *(22)*. Decreases in lung compliance of up to 50% have also been reported in infants less than 12 months of age utilizing insufflation pressures between 12 and 15 mmHg *(17)*. Furthermore, increased IAP significantly decreases tidal volume (17) and so in combination these derangements in ventilatory parameters may have serious consequences especially as paediatric ventilators are pressure cycled, and thus careful monitoring is warranted in order to prevent hypoventilation and hypoxemia which is not an infrequent occurrence as assessed by non-invasive monitoring using pulse oximetry. Hypoxemia is usually mild to moderate even in neonates and can be easily corrected by increasing minute ventilation and using positive end expiratory pressure *(1,17,18)*. It is worth noting that sudden onset of hypoxemia in patients undergoing renal procedures may indicate development of pneumothorax. This complication, although rare, has been reported in paediatric patients, developing as a result of direct injury to the pleura in relation to trocar placement and dissection, or may in this patient group be the result of gas moving through unrecognized congenital defects between the peritoneum and pleura such as diaphragmatic defects or pleuroperitoneal fistulas *(28–30)*. In adults risk factors for developing pneumothorax include operative durations of above 200 minutes, retroperitoneoscopic approach and an ET CO_2 >50 mmHg *(27,31)*.

Despite the detrimental effects of laparoscopy on pulmonary function, an overwhelming majority of clinical studies have found laparoscopy in the paediatric age group to be safe. Overall, laparoscopy even seems to confer respiratory benefits in terms of improved rates of extubation, shorter recovery room stays and shorter durations of chest physiotherapy when compared to open surgery *(32)*. So pulmonary changes that, in absolute terms significantly worsen with laparoscopy seem to have minimal clinical impact as long as proper anaesthetic monitoring is maintainedThis also holds true for neonates in whom on table extubation was possible in 60% of patients in one study *(1,18)*.

4. CARDIOVASCULAR RESPONSE

As there is close relationship between the cardiovascular and pulmonary systems, it is no surprise that the effects of abdominal insufflation are to be felt here. The cardiovascular response to increased IAP can be complex and depends on a multitude of factors such as preload, systemic vascular resistance, myocardial contractility and their interplay with different levels of IAP and patient position. Furthermore, hypercarbia may influence the cardiovascular system indirectly via activation of neurohormonal pathways. Therefore the resultant cardiovascular effect depends on the prevailing circumstances and cannot always be predicted in advance. In adult studies increased IAP leads to increases in systemic and pulmonary vascular resistance in addition to increases in mean arterial pressure. Heart rate remains largely unaffected by PnP whereas cardiac output decreases by up to 30% *(33,34)*. Similar outcomes have been reported in different paediatric age groups albeit with some deviations. In 6–30 month old boys undergoing laparoscopy for non-palpable testes at an IAP of 10 mmHg and in the horizontal position, Gueugniaud et al. using ultrasonic flow measurements reported a 30% decrease in cardiac output and significant decrease in stroke volume combined with an increase in systemic vascular resistance whereas blood pressure remained stable *(35)*. Similarly, in studies by Sakka et al. and Kardos et al. using slightly higher insufflation pressures of 12 mmHg, cardiac index (cardiac output indexed to body surface area) decreased 13% and 25% respectively, and there was in both studies concomitant increases in mean arterial blood pressure and systemic vascular resistance. Heart rate and stroke volume showed decreasing trends *(36,37)*. In the study by Sakka et al. IAP was lowered to 6 mmHg which resulted in normalization of the cardiac index and other cardiovascular parameters. Curiously, raising the pressure again to 12 mmHg did not alter the cardiac index as it initially had done *(36)*. Low pressure PnP of 5 mmHg in patients under 3 years of age has even been associated with a 22% increase in cardiac index, and significant increases in heart rate and mean arterial pressure *(16)*. These apparently conflicting results could be the result of different study designs and anaesthetic protocols. Patient positioning differed in the aforementioned

studies in that patients were in the supine position in the studies that showed decreased cardiac output whereas they were in the reverse Trendelenburg position in the study by De Waal that showed increased cardiac output. Another plausible explanation to the observed differences could be related to the different IAP used. It has been put forward that abdominal insufflation to pressures less than that of the right atrium leads to the squeezing of blood out of the venous capacitance vessels in the splanchnic circulation leading to an increase in venous return and thereby an increase in cardiac output. Insufflation pressures exceeding those of the right atrium would on the other hand lead to compression of the vena cava whereby preload decreases and which consequently translate into a decreased cardiac output. Additional increases in IAP would lead to compression of the aorta and splanchnic vessels hence increasing cardiac afterload which also would lead to further decreases in cardiac output *(16)*. Intravascular volume depletion is therefore to be avoided as it decreases preload and in combination with vascular compression caused by PnP may lead to a higher risk of cardiovascular collapse in dehydrated patients. In neonates and infants with congenital heart disease, use of excessive IAP may even lead to temporary or permanent reopening of intracardial shunts (foramen ovale or ductus arteriosus) increasing the risk of air embolism and heart failure *(16,38)*. Such occurrences have even been reported in adults undergoing laparoscopy *(39)*.

Other than its mechanical effects PnP most likely also affects the cardiovascular system indirectly by activating different neurohormonal pathways. Animal and adults studies show that PnP results in progressive and significant increases in plasma concentrations of cortisol, epinephrine, norepinephrine, renin, and vasopressin. Changes in vasopressin plasma concentrations closely paralleled the increases in systemic vascular resistance and seemed to be related to CO_2 absorption as Argon insufflation did not lead to a similar response. Administration of clonidine which is a known inhibitor of vasopressin release partially blunted this response *(33,40)*. Studies in paediatric age groups are lacking however similar mechanisms seem very plausible in children.

Based on the aforementioned studies an IAP of 6 mmHg in neonates and infants has emerged as the safe level at which cardiovascular derangements are avoided. It is however again to be noted that cardiovascular effects of PnP which in absolute terms may seem significant appear to have minimal clinical impact so long as infants are appropriately monitored as witnessed by a number of studies that have employed even higher levels of IAP and have reported stable cardiovascular parameters and no occurrences of hypotension *(17,35,41)*. There have even been reports of infants with congenital heart disease successfully undergoing laparoscopy at pressures of 12 mmHg *(42,43)*. The 6 mmHg level is therefore not intended as an absolute cut-off, but serves rather as a guideline.

5. RENAL RESPONSE

As postnatal renal function continues to evolve throughout childhood, benefits from laparoscopy would have to be weighed against any potential harm afflicted on the developing kidneys *(44)*. Studies concerning renal function in children undergoing laparoscopy are however lacking. Existing evidence stems from animal and adult studies and will therefore have to be cautiously extrapolated to the paediatric patient. Human studies and various animal models have consistently shown that PnP affects renal function. In a recent review of all relevant literature on this subject, Demyttenaere et al. found compelling evidence of a decrease in renal blood flow during PnP. This decrease was pressure dependent and was found to worsen with certain patient positioning such as the reverse Trendelenburg position. Furthermore it was noted that adequate hydration mitigated this decrease and that the type of insufflant was irrelevant. Looking at renal function and urine output the same paper detailed consistent evidence supporting a decrease in glomerular filtration rate and urine output during PnP. In both instances the changes were seen to be temporary normalizing upon exsufflation and of unclear clinical significance. It is however most likely that such changes were of no significant implication for healthy individuals *(45)*.

In a lone study elucidating the effects of PnP on urine output in children aged 7 days to 15 years, Gómez Dammeier et al. showed that an IAP of 8 mmHg resulted in anuria within 45 minutes of establishing PnP in 88% and 14% of children under and over one year of age respectively. Furthermore, 41% of the children older than 1 year became oliguric. Postoperatively, urine output increased significantly in a compensatory manner peaking at 5 hours post exsufflation *(46)*. Mechanisms underlying this transient dysfunction are most likely multifactorial and could be related to the mechanical effects of raised IAP which may directly compress the renal cortex and or the renal veins, in combination with the previously mentioned cardiovascular effects that ultimately lead to a decrease in cardiac output and stimulation of neurohormonal vasoactive pathways which in due course lead to decreased renal perfusion, and a fall in glomerular filtration rate and diuresis *(47,48)*. Again as in the adult population, the clinical relevance of these findings is unclear. In practice this should be kept in mind when calculating intravenous fluid requirements during surgery as urine output under these circumstances cannot be considered an accurate metric. Nevertheless, judging by practical evidence, healthy children seem to weather this transient renal impairment. Studies in children with impaired renal function are lacking and patently needed.

6. NEUROLOGICAL RESPONSE

The effects of PnP on the central nervous system have been thoroughly described in various animal studies. Creation of CO_2 PnP leads to prompt

and sustained elevations in intracranial (ICP) pressure that normalize upon exsufflation. Mechanisms underlying this increase include the mechanical effects of increased IAP which shifts the diaphragm in a cephalad direction narrowing the inferior vena cava and elevating intrathoracic pressure. This in turn leads to intracranial venous stasis and a decreased resorption of cerebrospinal fluid in addition to impaired drainage of cerebrospinal fluid at the level of the lumbar venous plexus. The increases in ICP are directly proportional to the level of IAP. Biochemically, the absorbed CO_2 which leads to varying degrees of hypercarbia induces cerebral arteriolar vasodilatation which further increases ICP. Trendelenburg position and hypoventilation also significantly increase ICP whereas diametric manoeuvres, i.e. reverse Trendelenburg and hyperventilation, only partially restore normalcy *(49–53)*. Using infrared spectroscopy De Waal and co-workers were able to show considerable increases in the cerebral blood flow of infants during low-pressure laparoscopy despite hyperventilation and having the patients in a head up position *(54)*. Laparoscopy is thus contraindicated in patients with head injuries or intracranial space occupying lesions *(55)*.

Another caveat pertains to patients with myelodysplasia, who in addition to their neurological disabilities often need substantial urological management. As the envelope continues to be pushed in paediatric urology these patients stand to benefit from an increasing number of complex surgical procedures that can now be completed laparoscopically, especially with the advent of robotics. A majority of these patients have, however, an associated Arnold-Chiari malformation obstructing the outflow from the fourth ventricle and requiring ventriculoperitoneal (VP) shunting for management of their obstructed hydrocephalus. Concern levelled at creating PnP in these patients has been rife, the obvious worry being that PnP may cause shunts to fail and in the worst case scenario lead to retrograde flow and pneumocephalus. Recent experience however shows that when adequate precautions are taken, presence of VP shunt need not be a contraindication. Clamping of the VP shunt, either intraperitoneally or by exteriorising the shunt, combined with regular exsufflation and pumping of the reservoir has been employed as a protective means *(56,57)*. Others reported the use of low pressures or invasive monitoring by measuring pressure directly from the shunt reservoir *(58,59)*. In the latter case the ICP increased rapidly to 25 mmHg upon insufflation and tapping of an average of 30 ml of cerebrospinal fluid was needed to restore ICP to what was deemed a safe level. Postoperative skull X-rays showed no evidence of pneumocephalus *(59)*. In the largest reported series of 18 patients with a mean age of 13 years, Jackman et al. using only non-invasive routine monitoring found no evidence suggesting clinically significant increases in ICP, and all procedures were completed successfully without event under an IAP of 12–20 mmHg *(60)*. VP shunts are designed with a one-way valve that only allows antegrade flow, this valve mechanism has been shown to withstand pressures of up to 350 mmHg before failing yet

structural distortion occurs already at about 80 mmHg. Both pressures are well above the clinically used ranges of IAP *(61)*.

7. THERMOREGULATION AND METABOLISM

Paediatric patients undergoing operative procedures are prone to developing hypothermia. Hypothermia occurs due to the effects of general anaesthesia and the radiative, convective, and evaporative heat losses incurred to the ambient environment of the operating theatre. Furthermore, loss of temperature occurs due to the cooling effects of irrigation and intravenous fluids. Thermoregulation in neonates is further compromised by the inability of newborns to respond to cold exposure by shivering and the fact that general anaesthesia inhibits non-shivering thermogenesis. Maintaining normothermia intraoperatively is of utmost importance as hypothermia is known to significantly increase perioperative morbidity, a fact long recognized by paediatric surgeons, and which has lead to the institution of routine precautionary measures such as use of forced air warmers, warmed intravenous fluids, and regulated temperate ambient conditions *(62)*. In contrast to open procedures, laparoscopy can be envisaged to minimize heat loss as procedures are performed in the confines of a sealed abdomen which prohibits evaporative heat loss and retains the energy resulting from use of diathermy and other exothermic devices. This presumption is however contested by reports from adult, paediatric and animal studies which have repeatedly documented that hypothermia is not an infrequent occurrence in subjects undergoing laparoscopy *(1,18,20,63,64)*. Kalfa et al. reported core body temperatures <35 °C in 25% of their infant patients at the end of laparoscopic surgery despite using external heating sources. By using a linear regression model they found a significant inverse correlation between the length of surgery and core body temperature. Temperature loss was calculated to be 0.01 °C for each elapsed minute of surgery *(18)*. By comparing the heat loss sustained by infants undergoing open versus laparoscopic pyloromyotomy, Holland et al. showed that the drop in core temperature was more pronounced in the laparoscopic group although this difference did not reach statistical significance *(65)*. Heat dissipation in laparoscopy is mainly linked to insufflation of large amounts of non-humidified cold CO_2 and to a lesser extent to the use of irrigation fluids *(63,64)*. CO_2 is usually insufflated at room temperature and will in large amounts cool the internal organs and hence core temperature. This is further compounded in cases of gas leak where the constant circulation and exchange of cold dry insufflated CO_2 results in evaporative heat loss. Heating and especially humidifying the insufflant has been shown to significantly counteract such heat dissipation *(63)*. It is therefore imperative that working ports are properly secured and airtight so as to minimize the amount of insufflant needed, which in itself

can be a challenge especially in neonates and micropremmies in whom the abdominal wall can be paper thin *(66)*.

8. SURGICAL STRESS AND IMMUNE RESPONSE

Laparoscopic surgery in both adults and children has been associated with superior cosmesis, less postoperative pain, and quicker convalescence when compared to open surgical procedures of similar surgical stress *(67–69)*. Other than the apparent difference in size of the surgical incisions, laparoscopy has been shown to significantly reduce surgical stress when directly compared to formal laparotomy and this is believed to be the main reason underlying these benefits. Using markers of surgical stress such as cytokines and C-reactive protein (CRP), studies in paediatric patients undergoing laparoscopy have shown a muted surgical response when compared to patients having open procedures with significantly less elevations of the proinflammatory IL-6 and CRP in the immediate postoperative period *(20,69)*. It has also been suggested that the obligate period of immunosuppression following surgery in children and which is characterized by decreased expression of class II Major Histocompatibility Complex (MHC) HLA-DR is less pronounced after laparoscopy *(70,71)*. MHC/HLA-DR plays an important role in processing and presenting bacterial antigens to T-Helper cells, so a decreased expression of this protein is associated with detrimental effects on the ability to combat postoperative infection, and the levels of expression which are inversely proportional to the magnitude of surgical stress have been directly correlated to postoperative outcome *(70,72)*.

Interest has recently focused on an unanticipated and for that matter unintentional immune modulating effect of laparoscopy. It is well established that the organism mounts an acute phase response in the face of surgery, trauma, or sepsis *(73)*. This response although mainly beneficial can overshoot and become overwhelming resulting in a systemic inflammatory response which if left unchecked leads to multiorgan failure and ultimately death *(74)*. In vivo and in vitro animal studies have shown that CO_2 PnP can attenuate this response by modulating the immune response to surgical trauma. This is mediated by a CO_2-dependent increase in levels of the anti-inflammatory cytokine IL-10 which in turn downregulates TNFα production. In vitro incubation of peritoneal macrophages in CO_2 demonstrated this as it resulted in less TNFα and proinflammatory IL-1 cytokine production in response to bacterial lipopolysaccharide (LPS) stimulation, than when macrophages were incubated in helium or air *(75)*. Similarly, it has been shown by Hanly et al. that induction of peritoneal sepsis by caecal ligation and puncture in rats resulted in an attenuation of the hepatic acute phase gene expression and preservation of circulating leukocyte volume in animals that had undergone the procedure laparoscopically using CO_2 PnP rather than helium or by means of laparotomy *(76)*. In another study by the

same group, pre-treatment of rats by inducing a short period of CO_2 PnP effectively increased surgical survival after a subsequent LPS contaminated laparotomy procedure *(77)*.

PnP-mediated immune modulation is the result of the local peritoneal acidifying properties of CO_2, as such a response has only clearly been shown in association with the use of CO_2 insufflation. Instilling acid into the peritoneal cavity resulted in a similar reduction of the inflammatory response to LPS challenge *(78,79)*. Other studies have been less categorical in their conclusions stating merely that CO_2 PnP better preserves the status quo with regard to the immune modulating mechanisms and parameters assessed, in that the end result of some of the modulated immune processes can be viewed as either being beneficial or detrimental to the host depending on the held interpretation of the overall complex immune cascade *(80)*. The same holds true for the study by McHoney et al. in which it was shown that children undergoing laparoscopic fundoplication may have had an immunologic benefit over those undergoing open surgery, albeit not unequivocally *(71)*. It remains, however, that the immune modulating effect of CO_2 PnP is an interesting phenomenon that needs further elucidation not least within the clinical realm and may have potential exciting prospects in the management of acutely ill paediatric patients who up until now are preferentially managed by conventional open surgery should need arise.

9. EFFECT ON TUMOUR SEEDING

The issue of whether laparoscopy has a beneficial or detrimental effect on tumour cell behaviour continues to be debated. Initial reports from the adult literature seemed to suggest a higher incidence of port site metastases as compared to open surgery, but with increasing experience a decline in that incidence was noted and the initial gloomy results were attributed to a learning curve phenomenon. Conflicting outcomes between clinical and animal experimental studies have also added to the confusion; recent human studies have generally found a favourable effect of CO_2 PnP on tumour cell behaviour whereas animal studies have noted the opposite when adult human tumour cell lines were studied *(81,82)*. Laparoscopic surgery is believed to affect tumour cell behaviour in several ways. Mechanically, PnP may lead to aerosolization of tumour cells which tend to seed port sites where gas has a propensity to leak *(83)*. Technically, excessive tumour manipulation and instrument contamination may lead to an increased risk of seeding *(81)*, and as mentioned previously there is the immune modulating effect of PnP. The reduction in postoperative immune suppression enjoyed by laparoscopy patients may translate into a better ability to combat residual tumour or spillage. On the other hand CO_2 PnP has also been shown to adversely affect peritoneal macrophage activity and thus may lead to enhanced tumour spread *(80)*. The metabolic effect of the gas used has also emerged as an

independent factor with studies showing that helium PnP may be superior to CO_2 with regard to inhibition of tumour cell proliferation both in vivo and in vitro *(84–86)*.

In a study by Schmidt et al. paediatric tumour cell lines of neuroblastoma, lymphoma, and hepatocellular carcinoma investigated in vitro showed significantly decreased proliferation when exposed to CO_2 for a short period of 2 hours. A similar exposure to helium decreased the tumour cell proliferation of neuroblastoma, lymphoma, and rhabdomyosarcoma. Both gases significantly altered tumour cell activity, and therefore the effects could not solely be ascribed to the pH modulating effects of CO_2 *(87)*. In vitro rat studies failed to reproduce these results as CO_2 PnP had no advantage over open surgery for retroperitoneally inoculated neuroblastoma cells *(88)*. Notwithstanding this, the same group reviewed 129 laparoscopic tumour-related procedures in children and found no instances of port site metastasis, this has since been confirmed by others *(89–91)*. Clinical implications of these phenomena remain however elusive and further studies are needed before the full extent of tumour cell modulating effects of PnP and the mechanisms involved are elucidated.

10. CONCLUSIONS

Abdominal gas insufflation in children as in adults prompts a chain reaction of physiological events that if overlooked could be detrimental to patients and outcomes. Understanding and appreciating these changes and their consequences by both surgeons and anaesthetists are key to safe successful laparoscopic surgery in children. And while most physiological alterations encountered relate to the immediate well-being of the patient, new interesting aspects continue to emerge which undoubtedly will have important clinical relevance in the not too distant future and may ultimately alter the conventional wisdoms held in paediatric minimally invasive surgery and select areas of paediatric genitourinary laparoscopy.

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3 Robotic Equipment and Instrumentation

Armine K. Smith and Jeffrey S. Palmer

Abstract The advancement of laparoscopic robotic surgery largely depends on the development of innovative laparoscopic instrumentation. The most widely used system, the da Vinci surgical robot (Intuitive Surgical Inc., Sunnyvale, California), was introduced in 1998 and received FDA approval in 2000. Its popularity may largely be attributed to the development of EndoWrist instruments with increased degrees of freedom and improved stereoscopic vision. The electronics integrated into the system allow motion scaling of surgeon hand movement into smaller instrument tip movements in the field, reducing natural tremor of surgeon's hands. Instruments have a total of six degrees of freedom plus grip, mimicking the up and down and side-to-side flexibility of human wrist. Recently da Vinci S system has introduced (Intuitive Surgical Inc.), which features easier docking, added system feedback and high-definition telemonitoring. Another feature of the new S system is the additional 2 inches of length of the instruments.

The combination of pure laparoscopic and robot-assisted tools constitutes a standard approach to the advanced endourological techniques.

There are many available tools at the disposal of the robotic surgeon. Similar to the surgeon performing open surgery, a robotic surgeon's familiarity with available equipment and technology is essential. This knowledge of all the available tools is essential to the surgeon in maximizing the outcomes of the surgery and shortening the procedure times.

Keywords Equipment · Instrumentation · Laparoscopy · Robotics · Pediatrics

1. INTRODUCTION

The advancement of laparoscopic robotic surgery largely depends on the development of innovative laparoscopic instrumentation. The list of

available equipment has become exponentially longer since the first urologic implementation of robotic technology in the late 1980s. The combination of pure laparoscopic and robot-assisted tools constitutes a standard approach to the advanced endourological techniques. The knowledge of all the available tools is essential to the surgeon in maximizing the outcomes of the surgery and shortening the procedure times.

2. DEVELOPMENT OF ROBOTICS

The first generation of surgical robots used in urology (Puma 560, SARP, Probot, SPUD), introduced in 1988, consisted of rigid frame devices guiding a moving blade to complete transurethral resection of the prostate. The next level of surgical manipulators was marked by 1993 FDA approval of Automated Endoscopic System for Optimal Positioning (AESOP) (formerly Computer Motion Inc., Berkeley, California, now Intuitive Surgical Inc., Sunnyvale, California), which still remains widely used *(1)*. It consists of a table-mounted robotic arm, which may be used to hold a laparoscopic camera or retractor. It is controlled by the primary surgeon either by hand, foot, or voice, and allows for steadier field of vision and may even eliminate the need for an assistant. A similar free-standing laparoscopic camera manipulator, EndoAssist (Armstrong Healthcare, High Wycombe, UK), was introduced in 1990s, which is controlled by infrared signals from the headset worn by the surgeon.

The next generation of surgical robots introduced the "master–slave" concept. A master unit, controlled by surgeon, creates the command to be processed by a computer and sends it to the "slave" component, which then executes the task in real time. The ZEUS (Computer Motion Inc.) is the first such system, introduced in 1997 *(2)*. It consists of two physically separated subsystems: the executing system comprised by three arms that independently attach to the operating table, one of which is a voice-controlled AESOP, and surgeon's console with flat monitor and joysticks, providing control of the arms. A variety of 3.5 and 5 mm laparoscopic instruments with MicroWrist articulating tips can be connected to the robotic arms, including graspers, scissors, and hook. The more recent versions of ZEUS utilize a newer imaging system, which uses two separate videocameras and polarizing glasses worn by surgeon, causing a 3D image to be projected from the video monitor. In 2003, the makers of ZEUS merged with Intuitive Surgical, the makers of da Vinci® system, and as a result, this system is now no longer being offered for sale *(3)*.

3. DA VINCI SYSTEM COMPONENT OVERVIEW

The most widely used surgical robot, the da Vinci® surgical robot (Intuitive Surgical Inc., Sunnyvale, California), was introduced in 1998 and received FDA approval in 2000 *(4)*. Its popularity may largely be attributed

to the development of EndoWrist instruments with increased degrees of freedom and improved stereoscopic vision. The electronics integrated into the system allow motion scaling of surgeon hand movement into smaller instrument tip movements in the field, reducing natural tremor of surgeon's hands. Instruments have a total of six degrees of freedom plus grip, mimicking the up and down and side-to-side flexibility of human wrist (Fig. 1). Recently da Vinci® S™ system has introduced (Intuitive Surgical Inc.), which features easier docking, added system feedback and high-definition telemonitoring. Another feature of the new S system is the additional 2 inches of length of the instruments.

Fig. 1. *EndoWrist*® instruments have a total of six degrees of freedom plus grip, mimicking the up and down and side-to-side flexibility of human wrist.

The three components of the system are the console, surgical manipulator, and vision cart (Fig. 2). Master grips on the console provide control of robotic arms using thumb and forefinger motions (Fig. 3). The 3D view is projected to the stereo viewer integrated in the console view port at 10-fold magnification. Status message screens are projected onto the viewer through text and icons. The functions that are used during the procedure, but not while operating, are located on the armrest, on the user switch and interface panels. The ready button with instruments installed, camera selected and activation of the head sensor in the view port, engages the surgical arms to follow the commands of the masters. Several safety features are incorporated in the system, for example, if the head sensor is not activated, robotic

Fig. 2. The three components of the *da Vinci*® System are the surgeon console, patient-side cart, and vision cart.
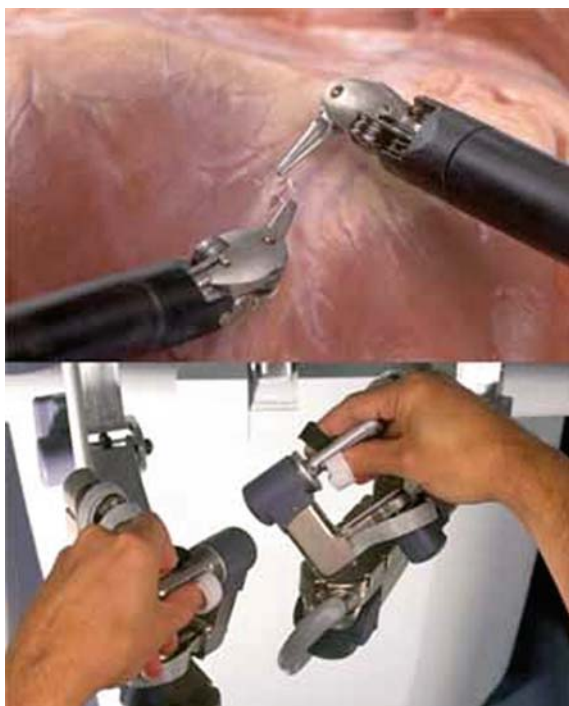
Fig. 3. Master grips on the console provide the surgeon to control robotic arms and instruments using thumb and forefinger motions.

arms would not move, even if the ready button has been pressed, or if the operator is absent for more than one minute, the system transitions into the standby mode. The interface panel uses a system of lights and buttons for the initial setup of console (Fig. 4).

Those functions that require access while operating are located on the foot switches at the base of the console. The clutch pedal moves the masters without moving the instrument arms, thus allowing the repositioning of masters for maximum comfort of operator's hand motion, similar to lifting a computer mouse off the pad, without relocating the cursor on the screen. Pressing of camera foot switch connects the masters to the camera arm, resulting in movements of camera arm. Focusing of the camera itself can be achieved by activating the focus pedal, located in the middle of the console foot base. Lastly, the "coag" pedal activates the application of coagulation energy to the tip of the instrument in use.

The processing tower holds the camera control unit, image recording device, camera light source, laparoscopic insufflator and monitor, providing

Surgeon's Console

Fig. 4. The interface panel uses a system of lights and buttons for the initial setup of console.

2D vision for the assistants. The patient-side manipulator is a mobile cart with three of four mounted robotic arms, one of which holds 0 or 30 degree binocular lens endoscope. If the system had three arms, the fourth one could be added at anytime. The arms are equipped with two flexible joints, the proximal of which moves in the up/down, sideways, and rotational axis (Fig. 5). The most distal joints of the instrument arms are capable of forward and backward motion. This allows manipulation of the arm position by the assistant located at the operating table, using joint release buttons, located on the robotic arms. Initially, the cart is sterilely draped away from the operating table. After the initial access is obtained, it is then rolled close to the patient and docked in the position, which then allows the endoscope and instruments to be mounted onto the adapters located on the robotic arms (Fig. 6) *(5)*.

Fig. 5. The arms are equipped with two flexible joints, the proximal of which moves in the up/down, sideways, and rotational axis.

4. ACCESS

The initial access to the peritoneal cavity is not different from standard laparoscopy and may be obtained in a variety of ways. The traditional approach uses Veress needle insufflation, followed by blind insertion of a blunted cutting trocar. Other approaches include using visual obturators, dilating tip trocars, balloon port inflation and open Hasson cutdown technique. All of these approaches carry a risk of tissue and organ injury, which is however minimized with the correct use of instruments and a proper selection of patients for the variations of the accomplishing access.

Trocars or ports come in a variety of designs and sizes. Standard laparoscopic 5, 10, and 12 mm and da Vinci 5 and 8 mm trocars have been developed in bladed and bladeless forms. Since blind insertion of a bladed
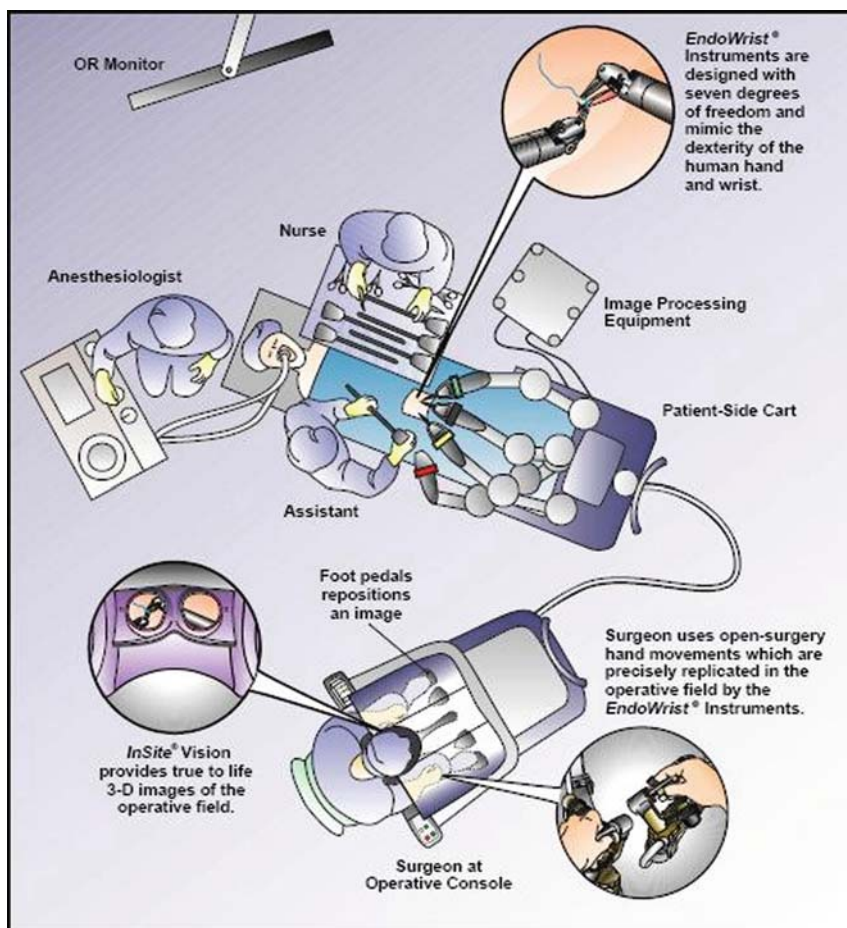
Fig. 6. After the initial access is obtained, it is then rolled close to the patient and docked in the position, which then allows the endoscope and instruments to be mounted into the adapters located on the robotic arms.

instrument carries the highest risk of blood vessel and organ laceration, which cannot be reliably be prevented by transillumination of the abdominal wall, the safety measure is to use either blunt trocars or bladeless forms for the initial penetration or in the areas of the body that have the closest proximity to vital structures. Defects in the fascia created by bladed 10 or 12 mm trocars require closure to prevent hernia formation *(6)*; however, blunt access with a similar port size creates a gap in the fascia that is smaller than the diameter of the trocar, and may therefore not require fascial closure. Bladed trocars may also be blunted extracorporally by touching the tip to the folded towels; caution must be applied not to loosen the grip on the instrument after the initial blunting, since this will cause reactivation of the blade.

The disadvantages of the blunt access include higher force application to the tissues during penetration.

Visiport (USSC, Norwalk, Connecticut), Optiview (Ethicon Endosurgery, Cincinnati, Ohio) and EndoTIP (Karl Stroz GmbH & Co. KG, Tuttlingen, Germany) systems combine the laparoscopic camera inserted in the trocar sheath to obtain visualization of the abdominal wall layers during the access. Usually, this is performed after initial insufflation of the abdomen; however, this is not mandatory.

Existing data do not show any advantage of Veress needle approach over the open cutdown technique for the initial access in the average population *(7,8)*. However, the Hasson technique is safer for patients with multiple surgeries, pregnant women, obese patients, and very thin patients, which includes the majority of pediatric population *(9)*. Subsequently, many pediatric laparoscopists use the open Hasson method of initial access. With this technique, the fascia and peritoneum are opened via a small skin incision and a trocar is then inserted into the peritoneal cavity or retroperitoneal space. The trocars that can be used with this technique are the STEP system (USSC), which consists of a mesh sleeve over a Veress needle, which then may be dilated to the desired diameter, and Preperitoneal Distention Balloon System (USSC) or Spacemaker II Balloon Dissector balloon dilators (USSC), which mainly find their use for retroperitoneal surgery. The disadvantages with the Hasson method are the leakage of gas from a larger incision and difficulty of dissecting and identifying fascia in obese individuals.

5. INSTRUMENTS

5.1. Tissue Handling

The main formula for surgical success, including laparoscopy, is the knowledge and use of available instruments that offer the maximum dexterity for the surgeon. Since the invention of the first robotic system, the number of available tools has increased exponentially. However, many surgeons have experience with only a few early generation robotic instruments, which may limit their operative options. Currently, a variety of da Vinci and da Vinci S instruments are available in 8 and 5 mm sizes *(10)*. They differ by the length and force of opening and closing of the working element and additional functionality. The most commonly used tissue graspers in urological procedures are presented in Table 1. Depending on the force of closure, these graspers may cause variable damage to the tissue. Therefore, the instruments with the lowest closing force are used for more delicate tissue handling. High opening force can be advantageous if tissue dissection is desirable. Longer jaw length and higher opening angles provide advantage in situations where thick or redundant tissue needs to be handled, like bladder wall. Another advantage of using instruments with longer jaw is that

Table 1
Tissue Graspers

Instrument name	Port size (mm)	Jaw opening force	Jaw closing force	Length (cm)	Max. jaw opening angle	Additional features
Round tooth forceps	8	Low	Low	1.1	30	
Debakey forceps	8	Low	Low	1.2	30	
	5	Low	Medium	2.0	30	
Long tip forceps	8	Low	Low	2.0	30	
Cadiere forceps	8	Low	Low	2.0	30	
ProGrasp forceps	8	Very high	High	2.8	38	
Fine tissue forceps	8	Very low	Very low	1.1	30	
Resano forceps	8	Very low	Low	1.1	30	Atraumatic teeth
Bowel grasper	8	Very low	Very low	3.8	60	
	5	Low	Medium	3.9	30	
Double fenestrated grasper	8	Very low	Very low	3.3	60	
Cobra grasper	8	Low	Low	2.0	60	Terminal teeth
Tenaculum forceps	8	High	High	3.0	75	Used for grasping very thick tissue
PK dissecting forceps	8	Low	High	2.0	70	Bipolar sealant with audio feedback
Schertel grasper	5	Medium	Medium	3.2	30	
Maryland dissector	5	Low	High	2.7	30	
Bullet Nose dissector	5	Low	High	2.7	30	

they are 1–2 cm longer thereby improving the reach of the instrument, but sacrificing the force of the terminal grip. Instruments that are 5 mm in size compared to the 8 mm instruments have lower jaw closing force and smaller jaw opening angle due to their size limitation.

5.2. Cutting

Cutting can be done by scissors and blades. Scissors come in three different shapes. For 8 mm port, fine tip Potts scissors (Fig. 7) can be used along with Snap-Fit instrument with blue (pointed) and paddle (tapered) disposable blades. For both 8 and 5 mm ports, the available instruments are round tip and curved scissors, which are very similar in properties, but have a different shape of the blades. Curved robotic scissors, similar to the curved handheld scissors, have the ability to "hug the tissue," therefore making easier to carve the desired segment at an angle.

Fig. 7. For 8 mm port, fine tip Potts scissors can be used along with *Snap-Fit*™ instrument with blue (pointed) and paddle (tapered) disposable blades.

5.3. Hemostasis

5.3.1. ELECTROCAUTERY

Electric current is used extensively for hemostasis in all the types of surgeries. Based on the type of a device, current is generated in the mobile generator box, transferred to the active electrode and from there either through the patient and grounding pad to the generator in the monopolar design, or to the return electrode integrated in one instrument in the bipolar design. To improve the safety of the monopolar cautery, electroshield system using active electrode monitoring (AEM) is used extensively in the operating rooms. This system interrupts the flow of energy from the generator if stray currents are detected, thereby protecting the patient from inadvertent thermal damage outside of the surgeon's field of vision *(11)*. Another safety feature offered by the robotic system is the Hot Shears tip cover accessory, which minimizes the active surface of the electrode and thereby reduces the chance of electric contact with non-target structures. Even though the bipolar instruments are regarded as more precise and less likely to cause collateral damage

to the tissues, monopolar cautery is still used by the majority of laparoscopic surgeons. The preference in the use of these instruments is based in part on the prior experience of the surgeon.

Monopolar energy instruments include 8 mm Hot Shears (monopolar curved scissors), useful in the settings when sharp dissection and cutting is preferential, but the risk of bleeding is significant. Therefore supplementation by occasional thermal energy saves the operator the extra time required for switching between instruments. The cautery hook, available in 8 and 5 mm, allows retraction of the tissue while coagulating, achieving precise thermal application and avoiding melting of the tissue planes together. Another similar instrument is the 8 and 5 mm cautery spatula with pointed tip, useful for fine thermal dissection of tissues. All the 5 mm monopolar electrocautery instruments feature disposable snap-on tips.

Bipolar electrocautery instruments deliver energy to the target tissue between the active and return electrode blades, allowing precise application of the energy limited to the tissue between the tips of the instrument. In many settings, these instruments can be used as the left arm of the robot, improving efficiency by allowing simultaneous tissue grasping and retraction with thermal application. Precise, fenestrated, and fenestrated Maryland forceps (Intuitive Surgical Inc.) have the capacity for thermal coupling. They have a high force of jaw opening and closing, which makes them ideal for tissue dissection. The difference between the instruments is in the shape of jaws: Precise forceps have triangular tapered tips; fenestrated forceps are square-shaped; and, Maryland forceps have a curve in addition to the triangular taper. Micro forceps have very fine and short jaws and have a lower grasping force. All of the listed instruments are available in 8 mm diameter.

The 8 mm PK dissecting forceps (Intuitive Surgical Inc.) (Fig. 8) use electrothermal bipolar vessel sealing, an alternative bipolar energy form, which couples high current, and low voltage. The tissue impedance then triggers adjustment in the voltage generated by the instrument. Based on this trigger, once the tissue has sealed, the device cools the ligated tissue and then produces an audible tone to alert the operator.

5.3.2. ULTRASONIC INSTRUMENTS

A different form of energy current is delivered by ultrasonic mechanical vibration of the bladed instruments, generating energy to seal small-to-medium sized blood vessels. These instruments produce less smoke, less collateral spread and charring of the handled tissues *(12)*. The harmonic curved shears (Intuitive Surgical Inc.), which are available in both 8 and 5 mm diameters, have been shown to have the least collateral damage and fastest tissue transection times.

Fig. 8. The 8 mm *PK*^{TM} dissecting forceps (Intuitive Surgical Inc.) use electrothermal bipolar vessel sealing, an alternative bipolar energy form, which couples high current and low voltage.

5.3.3. CLIPS

The use of surgical clips is shown to be secure and shortens the overall procedure time. Standard metal clips utilize Endoclip medium and small clip appliers (USSC) and are available in 5–12 mm diameters. The robotic 8 mm small clip applier is designed to be compatible with Weck Hemoclip (Weck Closure Systems, Research Triangle Park, North Carolina) small titanium clips. The advantage of titanium is that it not lithogenic nor prone to encrustation when used in the urinary tract. Another variation of clips is made of non-absorbable polymer material. These are compatible with large standard laparoscopic or 8 mm robotic Hemolock (Intuitive Surgical Inc.) appliers. The locking clips are larger and have a wider opening angle, thus being able to incorporate a bigger segment of tissue and lock behind the application site. The disadvantage of plastic clips is their bulkiness and occasional inability to lock the jaws over fibrotic or thick tissues. To optimize the security of locking seal and to minimize the chance of tissue avulsion, it is recommended to leave a small cuff of tissue distal to the clip.

5.3.4. STAPLING DEVICES

If it is necessary to ligate or separate a long stretch of tissue, standard laparoscopic linear staples may be applied via accessory ports. The staples can be categorized into cutting and non-cutting devices. Those with a cutting feature have a knife that is released after stapling, leaving three rows of staples on each side of the cut. Staplers also differ based on an articulating

feature and length of the staple line. Alternatively, some staplers are able to accommodate linear loads of different sizes. The list of currently available staplers includes Endo GIA (USSC), Endopath (non-flex and flex) (Ethicon Endosurgery), and Multifire Endo (GIA and TA) (USSC).

5.3.5. VASCULAR CLAMPS

Temporary occlusion of a bleeding vessel or renal hilum may be achieved with the application of standard laparoscopic bulldogs (Klein Surgical Systems, San Antonio, Texas and Aesculap Inc., Center Valley, Pennsylvania), introduced endoscopically via 10 mm or larger port. The use of Statinsky clamps (Klein Surgical Systems) on hilar vessels is the other option, but their application requires availability of an additional access site.

5.4. Tissue Glues

A variety of hemostatic agents and tissue sealants has been used as an adjunct to standard surgical techniques. Although most of the applications are still off-label, urologists use these agents mostly for minimally invasive operations. Even though the most data for their efficacy exists for hemostatic use, suture line reinforcement, prevention and treatment of fistulae and urinary tract reconstruction present another area which may benefit of a tissue sealant use. Most widely used agents are classified as fibrin sealants, topical and matrix hemostats based on their mode of action. Fibrin sealants (Tisseel or Hemaseel, Crosseal and Vitagel) contain two major components, thrombin and concentrated fibrinogen, which replicate the terminal stage of the coagulation cascade when mixed together. The resulting clot forms more rapidly and reliably than clotting process under normal physiologic conditions. Of these agents, Tisseel (Baxter Healthcare, Deerfield, Illinois), contains bovine aprotinin thereby potentially causing anaphylaxis in patients with bovine sensitivity. Crosseal (Omrix Biopharmaceuticals Ltd, Israel) is an entirely human product-based sealant, but uses synthetic tranexamic acid, which was shown to cause neurological adverse effects in rats due to gamma-aminobutyric acid antagonism. Therefore, it is contraindicated in any potential contact with cerebral matter. Vitagel (Orthovita Inc., Malvern, Pennsylvania) uses autologous fibrin, thereby eliminating the risk of anaphylaxis with its application. However, due to it pre-formulation using donor fibrin, its use carries the need for advance preparation.

FloSeal (Baxter Healthcare) is a bovine-derived gelatin matrix containing granules cross-linked with glutaraldehyde, which swell upon the contact with blood to produce tamponade effect. Human thrombin is mixed immediately prior to application to provide framework for clot formation. Surgiflo (Ethicon Endosurgery) has an identical concept, but it is manufactured using porcine collagen and mixed with bovine thrombin. The advantages of Surgiflo include reduced cost and greater product yield from a single use. Bioglue (CryoLife, Kennesaw, Georgia) is a surgical adhesive composed of purified

bovine serum albumin cross-linked with glutaraldehyde, which targets tissue proteins independent from clotting cascade.

Topical hemostats include gelatins (Gelfoam, and Surgifoam), oxidized cellulose (Surgicel) and microfibrillar collagen (Avitene, Collastat, Superstat, Instat, Helistat and Helitene). Main component of Gelfoam (Pfizer Inc., New York, New York) and Surgifoam (Ethicon Endosurgery) is the porcine gelatin that adheres to the bleeding site and becomes a trigger for clotting cascade activation by trapping platelets in the uniform pores. Removal of the hemostat carries the risk of clot disruption and recurrence of bleeding. Oxidized cellulose provides a lattice for clot formation, without enhancing the clotting process, so it is ineffective for patient with coagulopathies or platelet dysfunction. Microfibrillar hemostats are composed of bovine collagen, and their effect is due to the stimulation of intrinsic coagulation cascade.

The majority of evidence for the use of various hemostatic agents comes from the renal surgery. However, as their use was shown to consistently minimize blood loss, the attention was turned to the application of tissue glues in the prostatic and urethral surgery as an adjunct to hemostasis and urinary tract closure. The results from case series demonstrated decreased operative time for vesicourethral anastomosis and reduction in the number of urine leaks when fibrin sealant was used in prostatectomy. Similarly, applying fibrin sealant over a suture line of urethroplasty reduced the time to catheter removal and improved wound healing (13,14).

Fig. 9. *SutureCut*[TM] driver (Intuitive Surgical Inc.) has a blade embedded in the stationary jaw, which allows cutting the suture after knot tying is complete.

5.5. Suturing

The major advantage of robotic-assisted surgery becomes evident during suturing. The mimicking of human wrist motions by robotic instruments allows a larger freedom of movement and easier manipulation of the suturing material, which consequently translates into improved precision of the tissue penetration by the needle and quicker knot tying. Most commonly used large needle driver has an intermediate grasping force and short jaw. If larger needles are used, 8 mm Mega and SutureCut needle drivers (Intuitive Surgical Inc.) can be employed to maintain a better control of the needle, since both of these instruments have larger jaws and firm grasp. Furthermore, SutureCut driver (Intuitive Surgical Inc.) (Fig. 9) has a blade embedded in the stationary jaw, which allows cutting the suture after knot tying is complete. The additional available 8 mm suturing instrument is the Black Diamond Micro fine forceps (Intuitive Surgical Inc.), which, as the name implies, have a slender jaw and gentle grasp, decreasing the chance of bending or breaking a small needle.

6. SPECIMEN RETRIEVAL

After the specimen is freed up, it may be placed into small or large Endocatch bag (USSC) for retrieval. The instrument can be passed through a port or directly into fascial defect after the removal of the trocar. A metal band opens the bag, and after pulling the extracorporeal string, which closes the bag and detaches it from the metal ring, the ring may be pulled back into handle. After this manipulation, instrument is removed, leaving the specimen in the bag in the area of interest for subsequent recovery.

7. CLOSURE

At the completion of the procedure, pneumoperitoneum is released and port sites are closed. The recommendation is to close fascia for port site openings larger or equal to 10 mm to prevent hernia formation *(15)*. In thin patients this may be done extracorporeally, however, in obese patients and with the availability of specialized closure devices, many surgeons prefer to perform the closure of peritoneal port fascial defects under laparoscopic direct vision. The list of available instruments includes Carter-Thomason suture passer (Inlet, Trumbull, Connecticut), Berci facial closure device (Karl Stroz GmbH & Co. KG) and Endoclose device (USSC), all of which follow the principle of introducing the suture into peritoneal cavity through sharp penetration of the fascia and the retrieval of the suture end with a second pass penetration on the opposite side of the defect *(16)*. Since these instruments are sharp, care must be taken during the passage of suture material to avoid damage to visceral structures.

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4 Advantages of Robotic-Assisted Laparoscopy

Walid A. Farhat and Pasquale Casale

Abstract The introduction of robotic surgical systems represents a further step in the evolution of endoscopic instrumentation. Initially, the robot was thought to be bulky for children, but the delicate robotic movements are ideal for the reconstructive surgeries children require, hence pediatric urology has embraced robotic technology. The systems enhance dexterity using internal software that filters out the natural tremor of a surgeon's hand, which becomes particularly evident under high magnification and may be problematic when attempting fine maneuvers in very small fields. The introduction of the da Vinci system to perform precise laparoscopic manipulations offers an opportunity to spread reconstructive laparoscopic skills among pediatric surgeons.

However, despite its numerous advantages, the surgical robotic has a number of general limitations. In pediatric surgery, the size and variety of available robotic instrumentation remains limited compared with those offered for standard minimal invasive surgery (MIS) and the huge size discrepancy between the typical pediatric patient and the size of the robotic system (i.e., its "footprint") can restrict the anesthesiologist's access to the patient. Herein we are providing the benefits of robotic technology in children.

Keywords Advantages · Benefits · Limitations · Laparoscopy · Robotics · Pediatrics

Minimally invasive laparoscopic procedures have become widely available for a number of different operations, not only in adults but also in children. In the past decade, technical advances, including endoscopic instruments and high-resolution cameras, have contributed to the widespread use of minimal invasive surgery (MIS) in children *(1,2)*. The introduction of robotic surgical systems represents a further step in the evolution of endoscopic instrumentation. These computer-enhanced systems offer three

dimensional visualization and significantly improved instrumentation, with motion scaling and a wrist mechanism that allows surgeons to perform complex reconstructive procedures. Although these specific advantages may also benefit pediatric patients, only a few reports of robotic repairs performed in children have been made.

The introduction of robotic surgical systems, such as the da Vinci system, represents an evolutionary forward step in endoscopic instrumentation. These computer-enhanced systems not only offer three-dimensional visualization and significantly improved instrumentation, but also allow the performance of fine microsurgical tasks using an advanced motion scaling and a wrist like mechanism *(3–6)*. Initially, the robot was thought to be bulky for children, but the delicate robotic movements are ideal for the reconstructive surgeries children require, hence pediatric urology has embraced robotic technology.

1. SURGICAL ROBOTICS

Czech playwright Karel Capek coined the term "robot" (from *robota*, meaning labor) in 1921, referring to autonomous machines that are capable of replacing human laborers. Although most surgical robots in use today are more appropriately termed computer-assisted telemanipulators, the term "robot" continues to be used.

Originally conceived as a military tool for remote surgical care of the injured soldier, surgical robots were introduced into clinical practice in the late 1990s to overcome the limitations of conventional laparoscopy, including difficulties with dexterity and challenges of two-dimensional optics. Since then, computer-enhanced robotic surgical systems evolved rapidly and are now being used for a variety of complex MIS procedures *(7–11)*.

Surgical robotic systems are divided into three groups according to the degree of direct control and interface of the surgeon with the system *(12)*.

1. Autonomous systems that perform a preoperative plan without any direct control from the surgeon. These systems are typically used in procedures which require repetitive and highly precise motions. They are most frequently employed for neurosurgery, urology, and orthopedic procedures. A urologic example is the PAKY-RCM system developed by the Johns Hopkins group. This consists of an automated needle advancement system for percutaneous renal access *(13,14)*.
2. Surgical Assist Device where both surgeon and robot share control. A well-known example of this system is the AESOP® (Automatic Endoscopic System for Optimal Position; Computer Motion, Inc., Goleta, CA) *(15,16)* AESOP was the first surgical robot approved by the Food and Drug Administration (FDA) and is comprised of a voice-controlled robotic arm that actively manipulates telescope/camera, eliminating the need for a human camera holder and the associated difficulties in directing camera placement.

3. Teleoperator or master–slave systems in which the function of the robot is completely controlled by the surgeon. In this system, each movement of the robot is fully controlled by the surgeon, whereby the slave unit is composed of robotic arms performing the surgery, whereas the master console is physically separated from the slave robot, thus giving rise to the term *teleoperators*. The two main robots in this class are the da Vinci® Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA) and the Zeus®system (Computer Motion, Goleta, CA). During the initial production, the Zeus instruments were 5 mm in diameter compared with 8 mm for da Vinci. This allowed the Zeus instrument much better access to the very small space available in infants. The Zeus platform is no longer in production, and the da Vinci surgical robotic system is currently the primary system used in pediatric surgical practice and has 5 mm instrumentation available.

The systems enhance dexterity using internal software that filters out the natural tremor of a surgeon's hand, which becomes particularly evident under high magnification and may be problematic when attempting fine maneuvers in very small fields. In addition, the system can scale movements such that large movements of the control grips can be transformed into smaller movements inside the patient *(17,18)*. During conventional minimal invasive approach, the instruments pivot around the fulcrum of the insertion point, thus movement in the surgical field is always opposite the direction of motion of the handle in the surgeon's hand. In the robotic surgical systems, there is electronic separation of the instrument tips from the handles which eliminates the effects of instrument length, minimizes the fulcrum effect, and restores a more intuitive non-reversed instrument control *(19)*. In addition to the restoration of proper hand–eye coordination, the surgeon sits in an ergonomic workstation designed to minimize physical strain and fatigue. Therefore, application of surgical robots provides substantial clinical progress to the field of pediatric laparoscopic surgery.

2. ROBOTIC PEDIATRIC UROLOGIC SURGERY

Robotically assisted operations are thought to be safe in both adult and pediatric patients *(8,20)*. In the laboratory setting, the use of robots resulted in quicker and more efficient performance of standardized laparoscopic exercises compared with the standard laparoscopic approach *(21,22)*. However, it is not clear whether the potential technical benefits offered by this new technique are relevant in the clinical setting, especially in children. The pediatric patient poses additional challenges, such as smaller operative fields and more delicate tissues that necessitate fine suture material is required for delicate anastomoses, thus making pure laparoscopic approach difficult *(23)*. For that purpose, pediatric surgeons most often use magnification in the

form of standard loupes (×2.5–×6.5) for open surgery. When performing MIS, telescopes that provide ×10–×15 with limited 2-dimensional image are routinely used. By acknowledging the several limitations of conventional endoscopic tools, such as limited instrument mobility or decreased ergonomics *(24)*, pediatric surgeons are using the robot to assist in their surgical approach. With the advent of a novel dual channel telescope, the optical system incorporated into the robotic system enhances visualization by providing a highly magnified 3-dimensional (stereoscopic) image that improves hand–eye coordination. This image magnification combined with tremor filtration and motion scaling allow delicate motions in small areas, thus enabling surgeons to perform MIS that otherwise could be performed only in the hands of advanced laparoscopic surgeons. Robotic technology assists the pediatric surgeon by (1) increasing dexterity and precision of movements, (2) restoring proper hand-eye coordination in an ergonomic position, and (3) improving visualization *(25)*. Initially, robotic surgery was thought to be not applicable to children before adolescence due to the smaller working spaces and the robot's size. Robotic-assisted laparoscopic (RAL) surgery has penetrated pediatric urology.

2.1. Evolution of Robotic Assisted Laparoscopy in Children

Despite refinements in laparoscopic instrumentation with needlescopic 3-mm instruments, application of MIS approach for UPJO in children has been limited *(26–28)*. Since its initial description in 1995, few reports of this operation successfully performed in children have been published *(29–33)*. The difficulty in acquiring the skills to perform advanced reconstructive procedures lie in the need for focused mentorship program in children *(34)*.

In children, laparoscopic reconstructive surgery such as pyeloplasty may be a difficult and tedious procedure. The space, whether intracorporeal or extracorporeal, is limiting the surgeon sometimes to perform the operation from very difficult angles and positions. Furthermore, free hand suturing using the available laparoscopic instruments is time-consuming and needs to be done by an expert hand *(35,36)*. Though the robot may occupy most of the extracorporeal space, the surgery is facilitated by the surgeon's dexterity using instrument arms with six degrees of freedom with a wrist-like motion scaling. The da Vinci system offers a magnified three-dimensional view of the operating field, and mechanical control of the camera provides a steady magnified view of the operative field allowing precise suture placement. An additional benefit is the tremor filtration that enables the surgeon to use his right and left hands equally while suturing the ureter. Most importantly, the surgeon performs the procedure in an optimal ergonomic position, thus reducing fatigue during these time-consuming operations. Though tissue handling without haptic (touch) sensation is still controversial, but with experience, the surgeon uses visual cues from the 2-dimensional monitor and can avoid tissue damage *(37,38)*. This allows in situ surgery with accurate

depth perception and tissue inter-relations to accurately depict the pathology and correct it without strain on the target organ. For example, the organ does not have to be pulled up through a tiny incision in the skin to undergo reconstruction. The reconstruction can be done with the target organ in its natural position and location allowing recognition of the interaction with its surroundings and pathology.

The introduction of the da Vinci system to perform precise laparoscopic manipulations offers an opportunity to spread reconstructive laparoscopic skills among pediatric surgeons. Robotic-assisted laparoscopy appears to reduce the learning curve of intracorporeal suturing (39,40). Though the robot docking and fine intraoperative adjustments before its use require some time, studies have reported decreased operative times with robotic-assisted pyeloplasty compared with standard laparoscopic pyeloplasty, presumably from the improved efficiency in completing the ureteropelvic anastomosis (41,42).

In pediatric urology, Peters et al. (43) were the first authors to successfully complete various complex urological procedures while emphasizing the need for development of a dedicated team approach to robotic surgery. In 2004, Padraza et al. (44,45) reported successful completion of appendicovesicostomy in a 7-year-old boy and a bilateral heminephrectomy in a 4-year-old girl. Although operating time was quite long, the authors concluded that the robotic interface facilitated dissection of the hilum and vessels of the kidneys.

Over the years, robotic pyeloplasty has become more popular highlighting the advantage in intracorporeal suturing, precise dissection, and handling of the tissues (46,47). When comparing the gold standard open approach to robotic, it was evident that robotic surgery is longer but safe and technically feasible with the benefit of significantly shorter hospital stay. The longer operation times in the robotic group became nearly equal to the open surgery group's time later in time (48). Similarly, Yee et al. have shown that robotic-assisted pyeloplasty is associated with shorter hospitalization but longer operative time compared to the open approach (49). Although, many other urological procedures (e.g., ureteric reimplantation, pyelolithotomy, and Mitrofanoff) were performed successfully, robotic-assisted pyeloplasty is considered the most commonly performed procedure up to date using this technology with a success rate equal to that of the open gold standard but with longer operating times ($P= 0.03$). However, the disadvantages were lack of tactile sensations and higher cost. When robotic surgery is used for retroperitoneal approach, Oslen et al. (41) reported a series of 65 pyeloplasties using the da Vinci robotic system. The mean age was 7.9 years and the mean operation time was 143 min. Conversion was required in 1.5% of cases and complications were seen in 6% of cases. In conclusion, when measuring outcomes, robotic-assisted laparoscopic pyeloplasty in children is more commonly used for transperitoneal approach and it provides equal efficacy to that of the open procedure. The benefits of the approach appear to include decreased blood loss, length of hospitalization,

and use of pain medication. Nevertheless, additional clinical experience and long-term follow-up is required to determine the true efficacy of this method.

3. CHALLENGES AND LIMITATIONS WITH THE ROBOTIC SURGERY IN CHILDREN

Despite its numerous advantages, the surgical robotic has a number of general limitations. The current size of the da Vinci surgical system is the most critical limitation for its application in pediatric surgery. The robotic surgical system requires a complex and time-consuming setup, necessitating specially trained operating room staff thus resulting in longer operating room times. Add to this the high price of the robot along with the costs of the system's unique instruments and general maintenance *(50)*.

In pediatric surgery, the size and variety of available robotic instrumentation remains limited compared with those offered for standard MIS and the huge size discrepancy between the typical pediatric patient and the size of the robotic system (i.e., its "footprint") can restrict the anesthesiologist's access to the patient *(51)*. More technological advances and development of 5-mm instruments and smaller 3-dimensional endoscopes will likely extend the application of robotic surgical systems to neonates and infants. Until then, when performing robotic surgery in young children determination of optimal port placement is a significant issue. Mistakes at this stage of the operation lead to delays from frequent instrument conflicts and can result in additional unnecessary incisions if the ports must be repositioned.

The absence of tactile feedback and the inability to regulate the force applied to the tissues are characteristic of most endoscopic surgical techniques *(52)*. When performing robotic surgery, the loss of force feedback (haptics) is a natural phenomenon. Surgeons usually rely on visual cues such as tissue compression and blanching, and suture stretch (e.g., knot deformation), to determine the tensile strength of tissue and sutures. Advances in integrating imaging into the available robotic systems may facilitate surgeon intuition during the planning of complex reconstructions and improves on haptic.

When initially introduced, the robotic systems were designed to complete a simple anastomotic suture line. Gulbins and colleagues *(53)* reported that 30 minutes were required to finish a 10-suture throw in training simulators. Development of novel devices for joining tissues or anchoring a surgical prosthesis, such as the Tacker spiral tack (US Surgical, Norwalk, CT), the Salute (Onux Medical, Inc., Hampton, NH), the Sew-Right and Ti-Knot systems (both from LSI Solution, Victor, NY), or the U-Clip Anastamotic Device (Coalescent Surgical, Sunnyvale, CA) may significantly reduce anastomosis and operating time.

4. CONCLUSIONS

Pediatric robotic urologic surgery has established its place in the pediatric surgical practice. Initial results are encouraging, with a decrease in operation times with experience. Almost all pediatric urological procedures have been performed successfully with a small percentage of conversions and complications. Most of the studies have found that robotic surgery enables more refined hand–eye coordination, superior suturing skills, better dexterity, and precise dissection. The initial cost is an important issue affecting widespread use. As the learning curve to perform laparoscopic reconstructive procedures is steep, the use of robotics in simple and common cases also will make the whole team more acquainted with the system, hence reducing set-up and operating times and cost. The gain in time is counterbalanced by the additional time required for system positioning, such that total time from skin incision until skin closure is similar in both groups. The ultimate acceptance of this technology will depend on issues such as size, efficacy, and safety of machines suitable even for neonates and infants. At present, the regular use of robots, because of high costs, is confined to highly specialized centers. The robots still have to demonstrate their cost-effectiveness before a widespread use can be advocated. Hence, a well-structured robotics program could be of great help in making this system a success. There are limitations to the application of robotically assisted surgery in pediatric surgery. The main limitation is the relatively large size of the robotic ports, which are 8 and 5 mm in size as previously described. Future technological improvements, including a smaller instrument size to 3 mm, incorporation of tactile feedback, and instrument tracking may permit application of this technique in younger infants for more advanced procedures.

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5 Robotic Surgery: Considerations for the Future

Sebastien Crouzet and Inderbir S. Gill

Abstract Robotic surgery stands on the threshold of novel innovations and advances. This involves the development of newer robotic systems, novel robotic applications, and the incorporation of image-guidance and augmented reality navigation systems. Herein, we describe some examples of these ongoing advances in robotic surgery such as flexible ureterorenoscopy, robotic laser surgery, and robotic-assisted single-port surgery.

Keywords Laparoscopy · Robotics · Pediatrics · Lasers · Single port · Flexible robotics

1. INTRODUCTION

Robotic surgery stands on the threshold of novel innovations and advances. This involves the development of newer robotic systems, novel robotic applications, and the incorporation of image-guidance and augmented reality navigation systems. Herein, we describe some examples of these ongoing advances in robotic surgery.

2. FLEXIBLE ROBOTICS: ROBOTIC URETERORENOSCOPY

The increasing use of flexible ureterorenoscopy for retrograde intrarenal surgery is the result of advancements in flexible ureteroscope technology, holmium–yttrium–aluminum–garnet laser lithotripsy, and ureteroscope accessories such as wires, baskets, and access sheaths. Significant technologic developments in flexible ureteroscopy include better deflection, improved optics, increased durability, and miniaturization *(1,2)*. Recently, a novel robotic catheter system (Sensei, Hansen Medical, Mountain View, Calif) has been developed for intracardiac electrophysiologic applications

(3,4). This device has been used in urology by modifying the software and catheter-guide configurations from original system designed for cardiac applications.

The novel robotic catheter system (Fig. 1) comprises the following components: (a) surgeon console, including the LCD display and master input device, (b) steerable catheter system, (c) remote catheter manipulator, and (d) electronic rack. The surgeon console consists of the master input device (MID), display monitors, user interface pendant, and electronic module. The MID is a three-dimensional (3D) joystick that the surgeon uses to remotely manipulate the catheter tip. The display monitor allows simultaneous visualization of the endoscopic and real-time fluoroscopic views. Facility also exists to incorporate and synchronize other imaging modalities such as computed tomography.
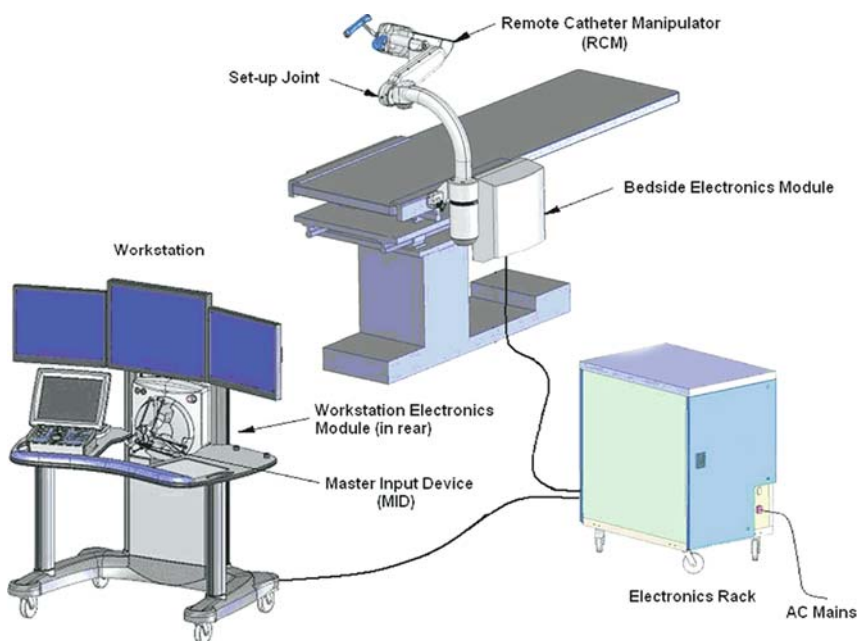
Fig. 1. Pictorial depiction of components of flexible robotic catheter control system. Surgeon console (workstation) showing three LCD screens, one touch screen, and MID.

The surgical console also includes a workstation electronics module that communicates with the electronic rack, controls the MID, and contains the workstation fault detection and mitigation hardware and software.

The steerable catheter system (Fig. 2) contains an outer catheter sheath (14F/12F) and an inner catheter guide (12F/10F). The movement of the MID intuitively controls the tip of the catheter guide.

The remote catheter manipulator (RCM) is the arm that attaches to the operating table on which the steerable catheter sheath and guide catheter are
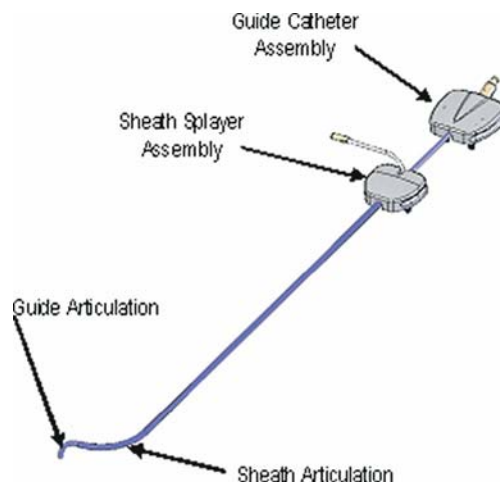
Fig. 2. Integrated sheath and guide assembly. Passive hollow fiberscope inserted through (inner) guide. Pressurized irrigant flows in through space between guide and outer sheath; space inside hollow ureteroscope allows fluid egress and also serves as working channel.

attached. The robotic system software has two modes in which the catheter guide can be manipulated: (a) a fluoroscopic mode and (b) an endoscopic mode that can be viewed simultaneously (Fig. 3) or readily interchanged by pressing a button on the console. In addition, it is possible to determine the

Fig. 3. Simultaneous fluoroscopic and endoscopic view seen by the operating surgeon seated at remote workstation. Note colored catheter animation provides visual clue to surgeon about direction catheter tip is attempting to take.

location and orientation of the ureteroscope tip in the collecting system by looking at the colored and shaded catheter animation on the LCD display.

This novel flexible robotic catheter system has the potential to further enhance the capabilities and efficiency of conventional flexible ureteroscopy. The Sensei remote robotic catheter system works on the principle of a master–slave robotic manipulator that allows precise, instinctive three-dimensional control of the tip of the steerable guide catheter remotely by appropriate manipulation of the three-dimensional joystick (MID) by the surgeon seated at the console. The maneuverability of the robotic system is not diminished by passing a 200 or 365-µm laser fiber. Recently, Desai et al. employed this system for performing robotic ureteroscopic laser lithotripsy in the clinical setting in 16 patients.

3. ROBOTIC LASER SURGERY IN UROLOGY

Several surgical lasers have been described, particularly in neurosurgery, where functional preservation of adjacent neural tissue during operative dissection is paramount *(5)*. The potassium–titanyl–phosphate (KTP) laser offers superior cutting qualities with minimal tissue penetration, typically <1 mm, while the neodymium-doped yttrium aluminum–garnet (Nd:YAG) laser offers improved hemostasis but with generally deeper tissue penetration *(6)*. Gianduzzo et al. from our group performed Laser robotically assisted radical prostatectomy (RARP) in 10 male dogs (19–35 kg). Specific prototype instrumentation was engineered for the study. As the green laser light saturates the camera system, 532 nm wavelength filters were incorporated into the camera adapter to prevent laser flare from obscuring the operative view. In addition, a prototype laser-delivery device was developed whereby a 5-mm da Vinci S instrument (Intuitive Surgical, Sunnyvale, CA, USA) was assembled to allow the passage of a 5 F ureteric catheter through the center of the instrument, through which a 300-µm endfiring Endostat® laser fiber (Laserscope, San Jose, CA, USA) was passed (Fig. 4). This instrument allows precise multidirectional delivery of the laser beam with complete absence of tremor.

All 10 procedures were completed entirely with the use of laser energy; the laser dissection was technically straightforward and proceeded efficiently (Fig. 5).

No additional hemostatic maneuvres, e.g. clips, US, or electrocautery, were required in any animal. Histological assessment of the excised acute specimens showed a zone of necrosis typically extending 0.5–1.0 mm from the cut edge of the prostatic fascia, extending focally to a maximum of 1.5 mm in some sections, with areas of injured but non-necrotic tissue up to 2 mm beyond the cut edge (Fig. 6).

Compared to our previous experience of laser dissection using hand-held laparoscopic tools *(7)*, the four-arm da Vinci S unit conferred distinct advantages. The absence of tremor improved the precision of the laser and enabled
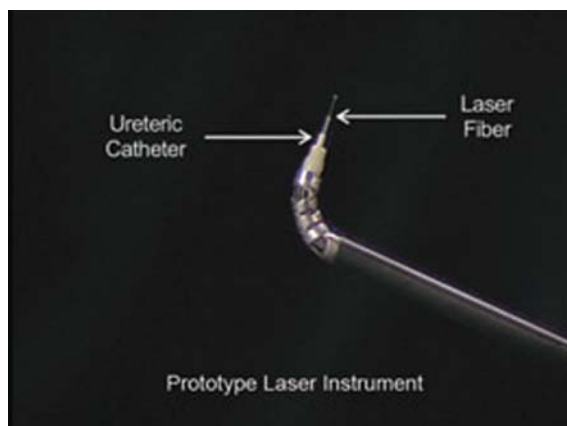
Fig. 4. The prototype 5-mm laser instrument, specifically designed to deliver a 300-μm Endostat end-firing laser fiber protected by a 5 F ureteric catheter.
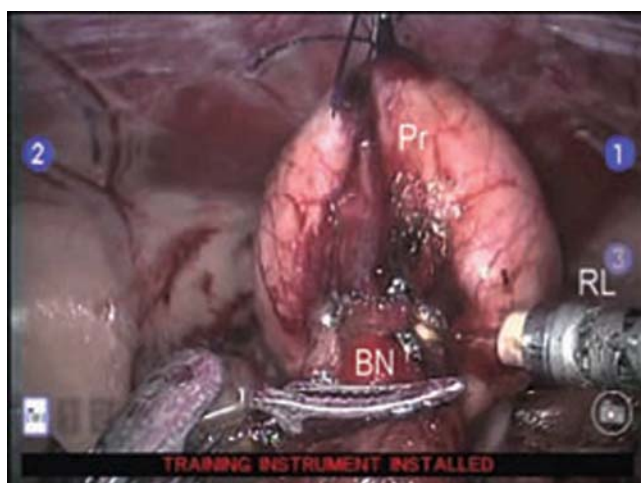
Fig. 5. Bladder neck division using the KTP laser delivered through a 300 μm Endostat fiber via the prototype 5-mm da Vinci laser instrument. Pr, prostate; BN, bladder neck; RL, robotic laser instrument.

narrow cutting widths to be achieved. As a result, lower power settings of 2–6 W could be used as opposed to the 6 W used with hand-held instruments in a previous study. In addition, the Endowrist® (Intuitive Surgical) technology of the laser instrument enabled the laser beam to be delivered from various angles, thus allowing the tissues to be specifically targeted, and therefore optimizing tissue cutting and vessel coagulation. The fourth arm
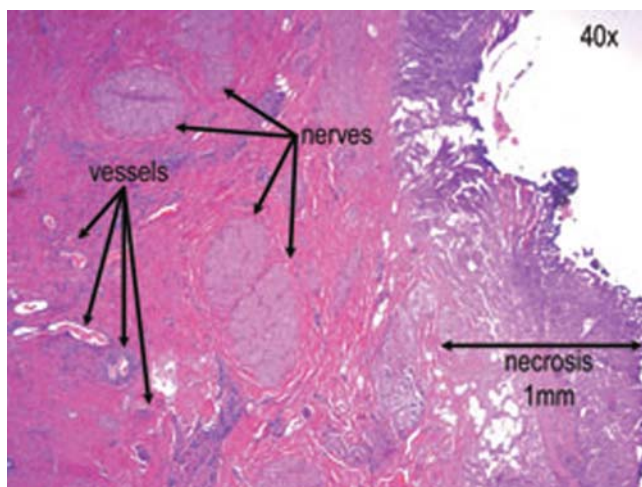
Fig. 6. A section of the lateral prostatic fascia showing the preserved neural and vascular elements, and acute laser-induced necrosis of 1 mm (hematoxylin and eosin, ×40).

allowed the operating surgeon to optimally retract the tissue for dissection. This, in conjunction with the laser tool, allowed the primary surgeon to operate with less reliance on the surgical assistant.

We have also performed laser robotic partial nephrectomy in five clinical cases without hilar clamping. The KTP-green light laser was employed successfully. Before wider clinical application of unclamped laser robotic partial nephrectomy can be recommended, two technical issues remain to be resolved: (a) smoke generation and (b) a reliable way to obtain hemostasis of the larger intra-renal blood vessels.

4. ROBOTIC-ASSISTED SINGLE-PORT SURGERY: TRANS-UMBILICAL AND TRANS-VAGINAL ACCESS

Kaouk et al. performed in 10 female farm pigs exploring a novel single-port access for robotic reconstructive urology. Our goal was to evaluate the technical feasibility of robotically combining trans-vaginal (NOTES) and trans-umbilical lapro-endoscopic single-site (LESS) surgical approaches. All animals underwent pyeloplasty followed by a radical nephrectomy on one kidney. The animal was repositioned and partial nephrectomy was performed on the opposite kidney. Thus, a total of 10 pyeloplasties, 10 partial nephrectomies, and 10 radical nephrectomies were performed, 5 of each procedure on the left side and 5 on the right side. A Single Port multicannula (Uni-X(TM) Pnavel Systems, Morganville, NJ) was used as an access portal through a single 2 cm incision in the umbilicus (Fig. 7). A 20 cm long, flexible, 12 mm cannula (US Endoscopy, Mentor, OH) served as a transvaginal port. The vaginal port was placed through the posterior fornix of the vagina

Fig. 7. Single port multicannula served as an access through the umbilicus and allows the insertion of the scope and the robotic cannula.

under laparoscopic monitoring. In the right-sided procedure the instrument in the left robotic arm and the laparoscope were placed through the umbilicus and the right robotic arm instrument through the vagina (Fig. 8). In the left-sided procedure the instrument in the right robotic arm and the scope were placed through the umbilicus and the left robotic arm instrument through the vagina.
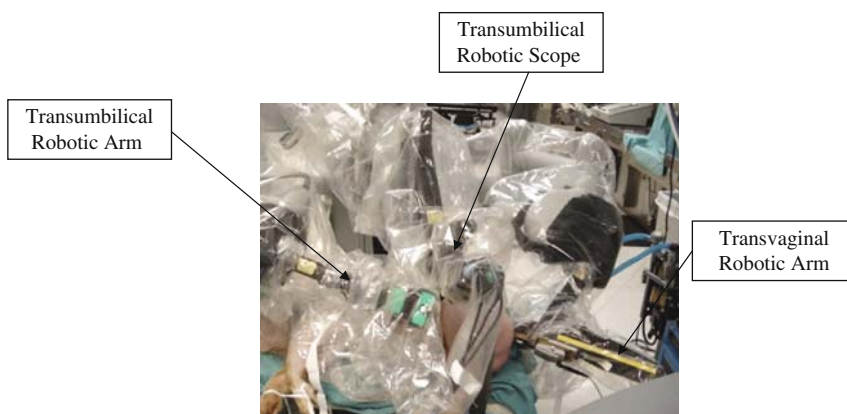
Fig. 8. Robotic arm placement.

All specimens were extracted transvaginally.

All 30 procedures were performed successfully without any additional laparoscopic port or open conversion. The mean incision size at the end of the procedures and after closure was 2.6 cm (range 2.4–2.9 cm).

No intraoperative complication was observed. No significant difference was found between the right side and the left side procedures when comparing operative time, pyeloplasty suturing time, partial nephrectomy warm ischemia time, estimated blood loss, and complications.

An interesting observation of this study was that the robotic system nicely compensated for the wide separation between the right and left robotic arms,

Fig. 9. Multi-channel single port.

Fig. 10. Surgical view.

giving the surgeon at the console the feeling of performing nearly rou-
tine robotic surgery. This experimental study represents an initial foray into
incorporating robotics into natural orifice (NOTES) and laparo-endoscopic
single-site (LESS) surgery.

Alternatively, a novel multi-channel single-port (R-Port) can be used
(Fig. 9). The Robotic scope and one instrument are inserted through the
single-port valves and the second instrument can be inserted on the side of
the R-Port through the same skin incision (Fig. 10).

5. ROBOTIC INTRALUMINAL SURGERY

Desai et al. have employed the da Vinci S surgical system for perform-
ing intraluminal surgery within the bladder using a single portal of access.
Specifically radical and simple prostatectomies have been performed using
this novel transvesical approach. The single-port used for this procedure
is the Quadport (ASC, Bray, Ireland), which was inserted percutaneously
into the bladder under cystoscopic control. The robot arms and scope were
inserted through the single-port (Fig. 11).
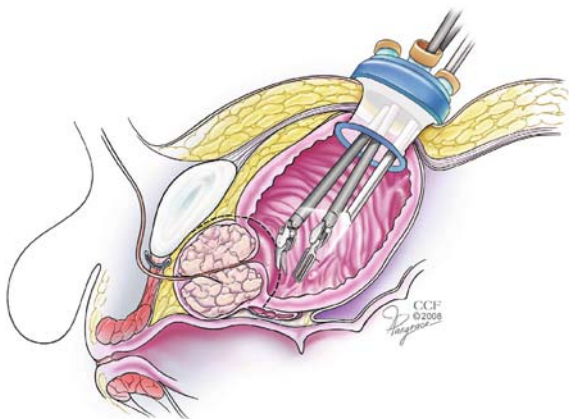
Fig. 11. Single-port and robot instruments through the bladder.

The articulated instruments and 3D vision facilitated precise dissection of
the prostate through a single-port. This initial experience opens the door for
intraluminal even trans-luminal, robotic applications in urology and other
surgical disciplines.

6. ENDOCONTROL ROBOT

A novel robotic system has been developed which can be used to drive
the laparoscope and articulated instruments, all inserted via a single portal

access. This introduces the concept of Single-port single surgeon robotic-assisted surgery.

Kaouk et al. performed a study on 4 male farm pigs, wherein 8 dismembered pyeloplasties (4 right and 4 left) and 8 partial nephrectomies (4 right and 4 left) were performed. The single port (TriPort, ASC, Bray, Ireland) was inserted into the umbilicus through a single incision. The scope was held and moved by a novel small light robot fixed on the OR table (Endo-Control, Grenoble, France) (Fig. 12). We used articulated instruments with deflectable and 360 degree rotatable tips that provide 7-degrees of freedom (CambridgeEndo, Framingham, USA) (Fig. 13).

Fig. 12. Robotic scope holder.

Fig. 13. Tip of the articulated instrument.

The robotic scope holder was installed around the single-port with the scope inserted through a 5 mm valve. The two other valves are used by the surgeon to insert two laparoscopic instruments (Fig. 14). The surgeon controls the scope movement with a foot-controlled pedal.

All procedures were performed without any additional laparoscopic ports or open conversion by a single surgeon. The mean incision size after closure
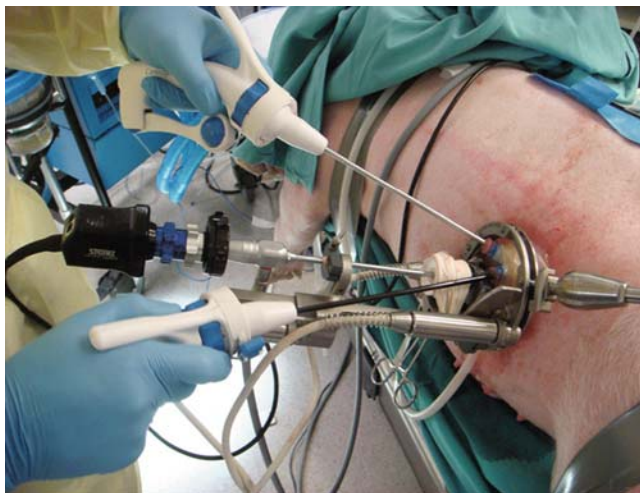
Fig. 14. Operating view.

was 2.7 cm (range 2.4–3 cm). The robotic endoscope holder with foot control provided a stable image with easy movements. Mean operative time for pyeloplasty was 112 min (range 95–130 min) and for partial nephrectomy 124 min (range 100–150 min).

The combination of a single-port, a robotic scope holder, and articulated instruments affords the potential for single-surgeon surgery. In this single-port format, the robot facilitated performance of the procedure.

7. COMBINATION OF ROBOTIC AND NOVEL TECHNOLOGIES

In order to improve the range and precision of minimally invasive surgery, combination of new technologies may be helpful. The main advantages of the current da Vinci robotic systems (articulation, 3D vision) can be reproduced by an alternative model which employs a combination of robotic-endoscope holder, 3D vision, and articulated instruments.

Our team examined this unique combination by performing a study on 10 farm pigs using:

- Articulated instruments: TheRadius surgical system (Tuebingen Scientific) provides 10 mm instruments with articulating tips controlled by deflection of the handle. A 360-degree rotation can be achieved by rotating the knob at the top of the handle (Fig. 15).
- 3D vision: The 3D vision is developed by Viking systems using a stereoscopic camera. The image is displayed on a novel 3D screen, 3D glasses, or a 3D display headset (Fig. 16).

Fig. 15. *Details of the articulated instruments.*

Fig. 16. *3D vision system in the operating room.*

Fig. 17. *Robotic scope holder.*

- Light endoscopic robot is a novel scope holder developed by Endocontrol medical with a foot control and voice control system (Fig. 17). It has a diameter of 110 cm, a height of 33 cm and a weight of 1 kg, it can perform a rotation of 360 degrees, an inclination of 70 degrees and a translation of 150 mm.

Combining these three technologies, 10 dismembered pyeloplasties, 10 urethrovesical anastomosis, and 10 partial nephrectomies were performed in the porcine model.

All procedures were accomplished successfully. The three technologies used herein were compatible and stable. No instrument failure was noted in any the procedures. The mean OR time for dismembered pyeloplasty was 84 ± 19 min, and 55 min at the end of the learning curve ($p < 0.0001$), estimated blood loss was 7 ± 4 cc. Tissue laceration and anastomotic leak on retrograde ureteropyelography were noted in the first three cases.

The mean suturing time for the urethrovesical anastomosis was 32 ± 9 min in order to place 8 sutures and suturing time was 20 min at the end of the learning curve ($p = 0.0004$). At autopsy, anastomotic leaks were noted on retrograde urethro-cystography in three animals.

The mean OR time for laparoscopic partial nephrectomy was 104 ± 30 min, warm ischemia time was 26 ± 6 min, and 19 min at the end of the learning curve ($p = 0.019$). Estimated blood loss was 40 ± 23 cc. Intra-operative complications included 1 renal vein injury which was suture-repaired laparoscopically. At autopsy, minimal tissue laceration were noted in the renal parenchyma in three animals.

8. ROBOTIC TRANS-RECTAL ULTRASONOGRAPHY

The TRUS robotic platform was developed by adapting the Endocontrol robotic endoscope holder (Endocontrol, Grenoble, France). A newly

developed software allows the robot to save the coordinates of up to 24 points. A commercially available TRUS probe (B-K Medical, Denmark) was used. Targeting accuracy between fiducial point A0 and targeted point A1 was measured three-dimensionally (∂x, ∂y, ∂z). The registration error was calculated as $\sqrt{(\partial x2 + \partial y2 + \partial z2)}$ using a tumor mimic and a prostatic calcification as a fiducial point on phantom and cadaver models, respectively (Fig. 18). The testing on the cadaver focused on (1) safety of movement, (2) complete visualization of the prostate in 2D and 3D, and (3) accuracy of targeting in human anatomy (Fig. 19).
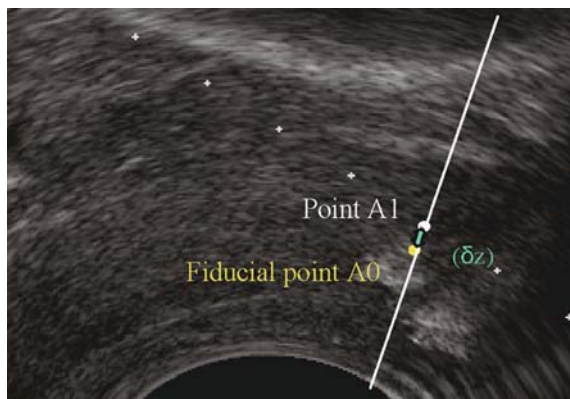
Fig. 18. Targeting accuracy.
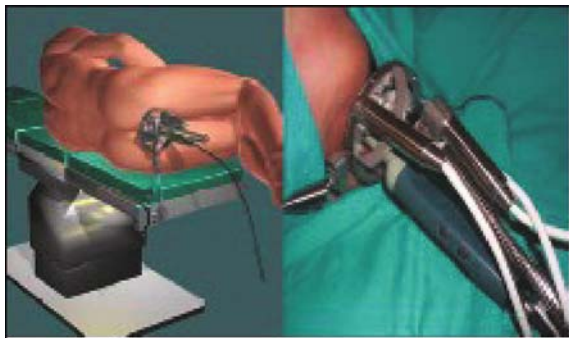
Fig. 19. Robot installation.

In the prostate phantom model, the registration errors ranged from 0.07 mm to 0.92 mm (mean 0.46 mm). Three consecutive targeted biopsies were successfully sampled in the tumor-mimic model. The set-up of the TRUS robot on the cadaver was straightforward. The robot successfully moved in a full range of motion. The entire prostate was visualized in 2D images, and automated 3D image acquisition was successful. The fiducial point registration error after 10 trials ranged from 0.23 to 0.90 mm (mean

0.58 mm). There were no unexpected movements, and no anal or rectal injury.

The initial testing of the TRUS robot on the prostate phantom and cadaveric model are encouraging. Robotic TRUS has the potential to perform accurate and reproducibly targeted biopsies and, in the future, potentially facilitate targeted focal treatment of prostate cancer. Robotic targeting using MRI and US fusion for real-time prostate tracking is ongoing.

9. IMAGING IMPROVEMENTS: AUGMENTED REALITY

The system consists of a computer and a localizer allowing spatial localization of the position of the various surgical instruments, using a magnetic sensor as well as an optical sensor (Figs. 20 and 21). Available imaging modality included real-time ultrasound as well as preoperative computed tomography (CT) or magnetic resonance imaging (MRI).
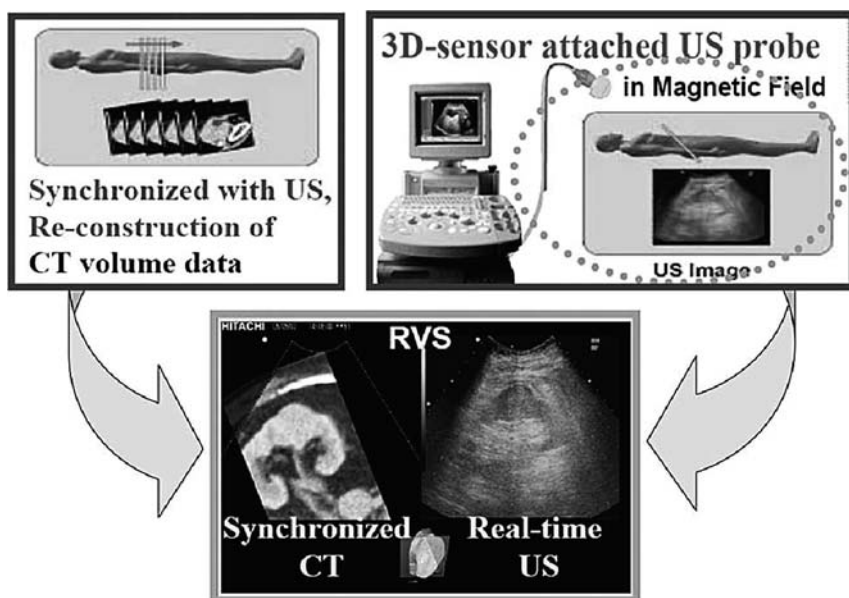
Fig. 20. Image registration and probe localization using magnetic field.

Clinically the fusion system of real-time US with preoperative CT or MRI has been applied for percutaneous radiofrequency/cryoablation for renal tumor. Augmented reality visualization system has also clinically been applied in laparoscopy for helping surgeons to understand 3D anatomy beyond the surgical view. Augmented reality was feasible and facilitated the surgeon's direct interpretation of 3D anatomy of cancer or vital anatomy beyond the surgical view, using preoperative CT data during laparoscopic
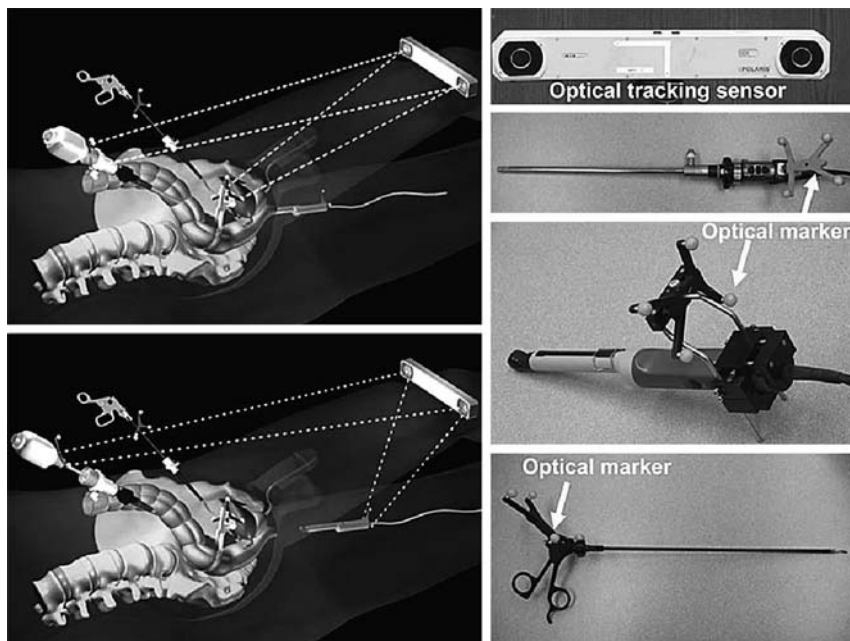
Fig. 21. Instruments tracking using optical sensor.

partial nephrectomy and intraoperative transrectal US during laparoscopic radical prostatectomy (Fig. 22).

Novel computer-based emerging techniques with 3D imaging technologies can potentially indicate the ideal dissection plane to achieve better oncological outcomes as well as to maximize functional preservation.

10. FUTURE POSSIBILITIES

The combination of multiple compact robots with incorporation of tactile feedback is currently under investigation (Fig. 23).

Future instruments are likely to be multi-tasking, by having a single device provide an articulating instrument, a laser fiber, a light source, and suction (Fig. 24).

Novel software can also potentially allow instrument tracking during surgery (Fig. 25).

11. ROBOT-ASSISTED REMOTE TELEPRESENCE SURGERY

The robotic surgical system combined with constantly improving telecommunication networking offer the potential of long distance remote telepresence surgery. Use of telepresence surgery at this time remains
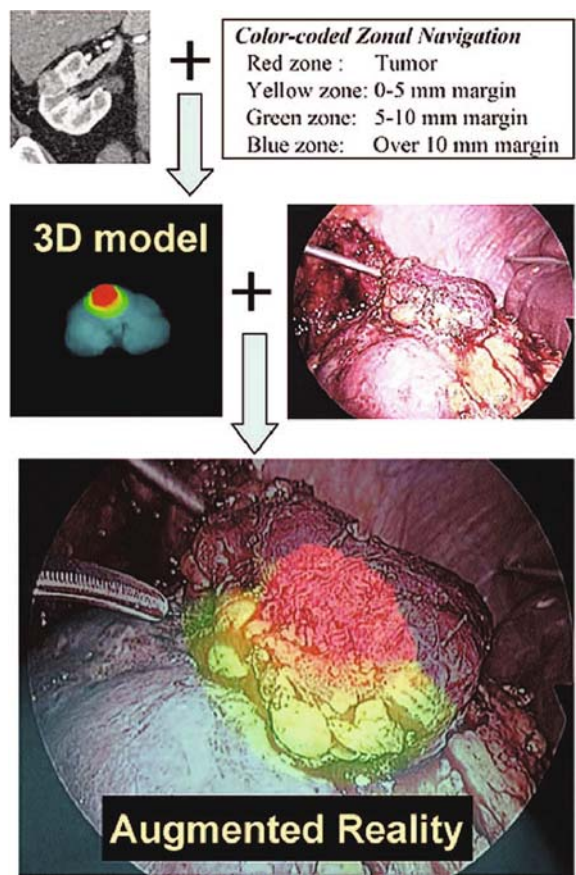
Fig. 22. Projection of the 3D preoperative CT data on the surgical view.
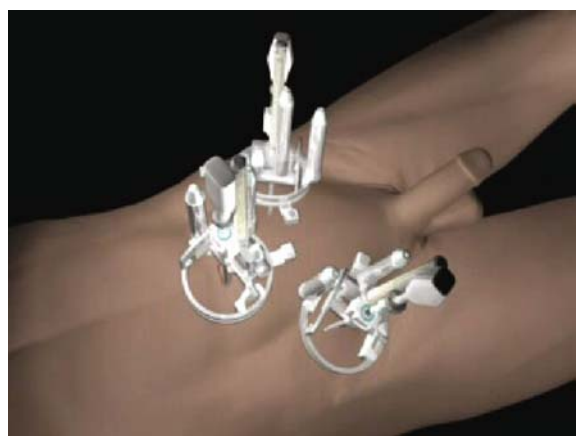
Fig. 23. Laparoscopic compact robot.
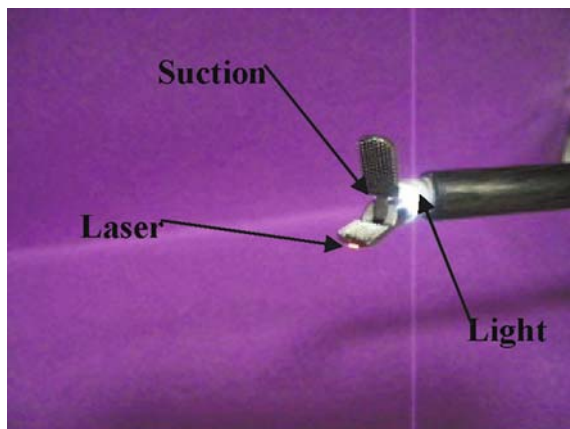
Fig. 24. Articulated instrument with laser, light, and suction.
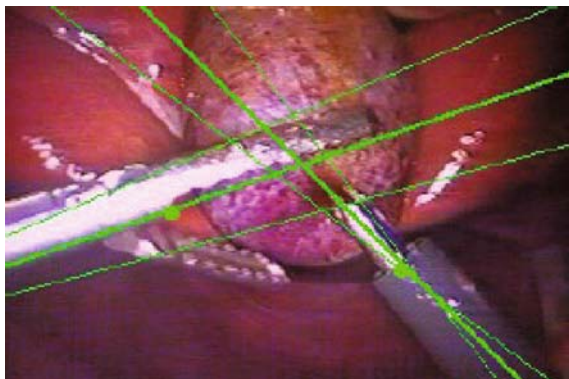
Fig. 25. Instruments tracking.

limited. The possibility of patient having their surgery done in their local hospital by a remote expert remains a possibility for the future *(8)*.

Future advances may include the replacement of scrub nurse and circulation nurse by robot, multitask and "intelligent" instrument, miniaturization, total autonomous system, optimum energy used, and biosurgery *(9)*.

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6 Transperitoneal vs. Retroperitoneal Laparoscopic Approaches

John C. Thomas

Abstract The application of standard laparoscopy to pediatric urologic surgery has clearly evolved over the past decade. One reason for the slower pace as compared to adult urology is that most cases in pediatric urology are reconstructive and require advanced laparoscopic skills. Despite these obstacles, advances in technology and increased reporting of patient series in the literature show that laparoscopy clearly plays a role in pediatric urology. Although robotic assistance offers some advantages over standard laparoscopy, there will always remain the choice of the most suitable way to reach the pediatric urinary tract, via either a trans- or retroperitoneal approach. This chapter will review each approach and highlight the respective advantages or disadvantages. In the end, the decision to apply what approach to which patient is based on the individual surgeon's experience.

1. INTRODUCTION

The application of standard laparoscopy to pediatric urologic surgery has clearly evolved over the past decade. One reason for the slower pace as compared to adult urology is that most cases in pediatric urology are reconstructive and require advanced laparoscopic skills. In addition, the rapid recovery of children from open procedures makes it more difficult to demonstrate a clear benefit of pediatric laparoscopy *(1)*. Despite these obstacles, advances in technology and increased reporting of patient series in the literature show that laparoscopy clearly plays a role in pediatric urology. The advent of robotic assistance has the ability to shorten the learning curve with advanced laparoscopic skills and potentially impact the ultimate outcome of

any particular procedure by offering improved visualization and greater precision *(2)*.

Although robotic assistance offers some advantages over standard laparoscopy, there will always remain the choice of the most suitable way to reach the pediatric urinary tract, via either a trans- or retroperitoneal approach *(3)*. The purpose of this chapter is to review these two approaches in terms of evolution, as well as inherent advantages and disadvantages. It will also describe direct comparisons of the two approaches in the pediatric population as described in the literature. It is important to remember that the approach in robotic surgery mirrors that of standard laparoscopy; however, there are certain challenges that arise in dealing with small infants and children. Basic approaches to each working space will be described; however, specific trocar placement will not be addressed as these will be described in detail in the subsequent chapters on surgical procedures.

2. TRANSPERITONEAL APPROACH

The transperitoneal approach is widely accepted as the easiest approach due to its large working space, familiarity of anatomy for most urologists, access to all retroperitoneal organs, and shorter learning curve *(4)*. An orogastric tube and Foley catheter should be placed to decompress the stomach and bladder prior to port placement. Access to the intra-abdominal cavity is established by either an open (Hassan) or closed (Veress) technique. The Hassan technique involves placement of a laparoscopic trocar through an infra-umbilical incision made under direct vision. The peritoneum is directly visualized and opened sharply to avoid inadvertent bowel or vascular access complications. It is helpful to pre-place fascial sutures to elevate the abdominal wall and facilitate closure of the port site. The trocar is then secured to the abdominal wall to minimize leakage of gas or significant subcutaneous emphysema. This technique can be applied to all cases or in cases where the Veress needle is contra-indicated, such as previous intra-abdominal surgery.

In contrast, the Veress needle has a solid spring-loaded stylet that retracts back only under pressure from firm tissue (i.e., fascia) to expose the sharp cannula; once the tip is free in the intraperitoneal space the stylet springs forward and protects against visceral injury *(5)*. Users of this technique describe two "pops" as the needle traverses the fascia, then the peritoneum. Proper position must be confirmed prior to insufflation. This is done by first aspirating through the needle with a saline-filled 10 cc syringe to ensure the needle is not inside the bowel or vessel. Then one should inject a small amount of saline into the abdomen and not be able to withdraw it. The syringe is then removed and the remaining drops of saline inside the Veress should enter the abdomen quickly and without resistance. Finally, once gas insufflation is commenced, pressure should remain low to confirm that the needle is not extraperitoneal. If the initial port is at the umbilicus, it is important to remember that bowel and large vessels are directly beneath the umbilicus and therefore the needle should be passed at a 45 degree angle. In obese

patients, the position of the umbilicus is more caudal and the Veress can be passed perpendicular to the incision *(6)*. Working ports are then placed under direct vision with the camera. In children, we prefer the Hassan technique in all patients.

Transabdominal laparoscopy does have several disadvantages. There is a higher chance for inadvertent thermal injury to the bowel. Also, there is a potential for greater cardiac and respiratory changes with this approach versus retroperitoneal surgery in terms of CO_2 insufflation *(7)*. In pediatric patients, smaller trocars are used; however, the incidence of trocar site hernias is increased with the transperitoneal approach and has been reported in ports as small as 5 mm *(8)*. Fortunately, partial nephrectomy for renal tumors is rare in the pediatric population, but if undertaken laparoscopically, tumors located on the posterior aspect of the kidney may be best served with the retroperitoneal approach. Some feel that transabdominal laparoscopy may increase the chance of developing adhesions or prolong post-operative ileus due to the irritative effects of the pneumoperitoneum; however, these notions have been debated *(9)*.

3. RETROPERITONEAL APPROACH

First reported in 1969 by Bartel, retroperitoneoscopy was felt to be limited by the small working space available and abundant fat in the retroperitoneum *(10,11)*. In fact, it is important to remember that the retroperitoneum is a potential, not an actual space, as compared to the peritoneal cavity *(12)*. In order to create a larger working space, Gaur reported the first use of a balloon device to expand the retroperitoneum in 1992 *(13)*. Numerous reports have shown this approach to be safe in the adult population as well as in children; however, those with experience always highlight the steeper learning curve involved.

The basic approach is with the patient in the lateral or 45 degree position, kidney rest elevated, pressure points padded, and table slightly flexed. It is also important to bring the patient to the edge of the table to avoid interference with the laparoscopic instruments, although this may be of less concern with the use of the robot. Initial access is generally obtained by making an incision off the tip of the 12th rib and using S-hook retractors to provide visualization through the tissue layers until the lumbodorsal fascia is encountered. The fascia can be pierced with a hemostat or finger and it is very important to direct the entrance into the retroperitoneal space anterior to the psoas fascia. Once proper position is achieved, the space can be developed with a trocar-mounted balloon dissector *(12)*. In smaller patients, an alternative to the balloon is filling a cut glove finger secured to a 12 Fr catheter with 150–200 cc of saline *(14)*. The anterior edge of the peritoneum is then further mobilized with manual palpation or under direct vision with the camera port in place. Subsequent working trocars are then placed depending on the operative procedure (see specific chapter).

The retroperitoneum can be accessed in the prone position as well. This was described by Borer et al. and involves entrance into the retroperitoneal space with an initial incision along the lateral border of the sacrospinalis muscle 1 cm below the costovertebral angle. Once the space is developed, one working port is placed midway between the tip of the 12th rib and the iliac crease along the posterior axillary line and the other port is placed just above the iliac crest at the lateral border of the sacrospinalis muscle *(15)*. These ports are placed under endoscopic guidance. The advantage to this position is the effect of gravity on the intra-abdominal contents and kidney, which fall ventrally and thereby allow easier access to the hilum, and avoid the need for bowel retraction. In addition, if emergent open conversion is needed, a dorsal lumbotomy can be readily employed *(15)*.

An advantage to retroperitoneoscopy is the protection from inadvertent bowel injury, although this should always be on the mind of the surgeon *(12)*. In the case of radical or partial nephrectomy, this approach allows for the most direct access to the renal hilum to secure vascular control. There may also be a theoretical decreased risk of prolonged ileus as compared to transperitoneal surgery, along with the fact that the risk of potential bowel herniation is eliminated *(16)*. Also, post-operative urinomas or hematomas are more easily contained. Retroperitoneoscopy can be safely used in patients with previous abdominal surgeries, and eliminates the risk for developing intra-abdominal adhesions.

Despite these advantages, identification of easily identifiable anatomic landmarks can be challenging during retroperitoneoscopy. Port placement is important as instrument interference is more likely with retroperitoneal laparoscopy as there is limited skin area available to place the ports, especially in small infants. Finally, there is debate on whether retroperitoneoscopy results in a lower risk of hypercapnia and one report showed a higher incidence of pneumomediastinum and/or pneumothorax *(16,17)*. Recurrent inflammatory processes in the retroperitoneum are a relative contraindication for this approach.

The ultimate challenge of this approach may be further exacerbated by applying it to infants and small children; however, these individuals do have less retroperitoneal fat present and most cases performed in children do not require a tremendous amount of working space. Specific to robotic-assisted cases, Peters states that it is preferable to develop the space, position the patient, and then engage the robot *(18)*.

4. TRANSPERITONEAL VS. RETROPERITONEAL LAPAROSCOPIC APPROACH—WHICH IS BETTER FOR PEDIATRICS?

A large prospective, randomized trial comparing these approaches with nephrectomy in adults has been reported. Time to hilar control and overall operative time was significantly shorter in the retroperitoneal group.

However, intra- and post-operative complication rate, hospital stay, blood loss, and narcotic use were similar no matter what approach was used *(19)*. In contrast, there is a paucity of literature in the pediatric population comparing these approaches in a prospective, randomized fashion. In fact, most series deal only with renal surgery. None the less, these reports do offer a comparison of standard laparoscopy from which similar conclusions may be made when approaching these cases with robotic assistance.

For example, retroperitoneoscopy was associated with longer operative times, which likely reflect the increased learning curve *(4,17)*. However, another series showed a significant decrease in operative time with the posterior prone retroperitoneal approach *(20)*. In a direct comparison of the lateral versus posterior retroperitoneal approach, Borzi stated that access to the renal hilum was easier with the posterior approach and that it was preferable for complete nephrectomy alone. In contrast, the lateral approach made it easier to remove ectopic kidneys and allows for a complete ureterectomy in all cases, especially in children >5 years old. It was noted that the lateral approach resulted in more inadvertent peritoneal tears and a higher incidence of pneumoperitoneum due to the thin infant peritoneum and the close proximity of the lateral peritoneal reflection *(21)*. There were no differences in hospital stay, analgesic requirements, and rate of complications in trans- versus retroperitoneal renal surgeries *(17,19)*. Some authors have suggested that patient age, not surgical approach, is an independent risk factor for complications. In a series of 48 children, Castellan et al. reported an overall 10% complication rate performing pediatric laparoscopic heminephrectomy with a trans- or retroperitoneal approach. Eight percent (4/5) of the complications were seen in children younger than 1 year old *(22)*.

5. CONCLUSIONS

Robotic-assisted laparoscopic surgery has clearly shortened the learning curve of standard laparoscopy and may ultimately provide better outcomes for our patients. Pediatric urology has adopted this technology and readily applied it to many complex operations as illustrated in this book. Both trans- and retroperitoneal laparoscopic approaches have their inherent advantages and disadvantages. Pediatric laparoscopy offers unique challenges to the operating surgeon in terms of patient size and complexity of the procedure. Until there is a prospective, randomized, multi-institutional study, it is impossible to say which approach is "better." In the end, the decision to apply what approach to which patient will be based on the individual surgeon's experience.

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7

Techniques and "Tricks of the Trade" of Robotic-Assisted Laparoscopy

Richard Schlussel

Abstract Robotic pediatric urology procedures are increasing both in number and in complexity. This chapter describes technical surgical considerations, patient positioning, and other "tricks-of-the-trade" for several surgical procedures including pyeloplasty, nephroureterectomy, and Malone Antegrade Continence Enema procedure (MACE). Also, a good surgeon is defined not only by intra-operative skill, but also by thoughtful pre-operative preparation. This is particularly true for robotic surgery. We also stress the importance of both facility with the use of the robot and practice on robotic devices in the laboratory. During practice sessions, the surgeon should not only practice suturing and knot tying, but also remember to do all exercises with both hands.

A good surgeon is defined not only by intra-operative skill, but also by thoughtful pre-operative preparation. This is particularly true for robotic surgery. When first using any new technology, one should select straight-forward, uncomplicated cases to avoid frustration and poor outcomes *(1)*.

This chapter will be mainly dedicated to technical surgical considerations. However, it is worthwhile spending a moment stressing ways to avoid the calamity of operating on the incorrect side. Most pediatric urologic robotic cases are "sided" surgeries. The surgeon should take several precautionary steps to make sure that all is accurately scheduled in the operating room. At the time of the operation, the operating room schedule, clinical notes from

the chart, radiologic studies, and radiologic reports should all be in accord as to the side and procedure.

Having access to the radiology images at the time of surgery is critical. It is also of great importance, in advance of the patient's arrival in the operating room, to discuss with the operating room staff the side of the surgery so that the robot can be positioned on the proper side of the room. This is much easier to do in advance of the patient's arrival in the room than trying to move the robot around the occupied operating room table.

Robotic pediatric urology procedures are increasing both in number and in complexity (2–7). Despite that, our surgical volume will never approach that of our adult urology colleagues who will perform many more procedures than we do (due in large part to robotic prostatectomy for prostate cancer). Hence our facility with the use of the robot should be supplemented with practice on robotic devices in the laboratory. Simulators are now coming to market for three-dimensional virtual reality training (8). During practice sessions, the surgeon should not only practice suturing and knot tying, but also remember to do all exercises with both hands.

The greatest robotic surgeon is ineffective without a team of nurses experienced in robotic surgery. Time taken to discuss the details of the case (which instruments will be needed, how they should be passed, etc.) is time well spent.

Positioning the patient is critically important. We place the patient in a modified flank position for renal cases. We bend the lower leg and have the upper leg straightened above it with a pillow between the legs. We place an axillary roll as well as a head roll. In order to keep the patient in this flank position we use a bean bag which solidifies when applied to suction. Alternatively, people have used a 30-degree wedge (9). In the past, we had brought the ipsilateral arm over the patient to reach the other arm. However, we now leave that arm out on its own side (as long as it does not create undue stretch) and have done so in order to create more working space for the robot arm up near the patient's upper abdomen. We have seen no untoward effects from this positioning. We also favor having the patient close to the edge of the bed as this allows wider excursion of the assistant's instruments (10).

We believe that placement of the Foley catheter at the beginning of the procedure is important, both for monitoring urine output and for later installation of methylene blue. We prefer to place the Foley balloon on traction at the bladder neck to prevent the uncommon, but possible occurrence of the guidewire passed from the kidney down the ureter, into the bladder and unintentionally coming out the urethra.

We prep the abdomen quite widely. In the case of a left-sided kidney procedure we have the patient in the left flank position and then ask the anesthesiologist to roll the table so that the left side is down. At this point, the abdomen is parallel to the floor which enables port placement more easily. The umbilical 12 mm camera port is developed. We begin with a curvilinear incision in the inferior aspect of the umbilicus and take this through the

fascia. Once through the fascia we open the peritoneum. It pays to do this incrementally and in fact even struggle a bit getting the trocar in as opposed to having a very large loose access to the peritoneum that may allow for a gas leak or trocar slippage out of the abdomen later in the case. Open access to the peritoneum has been shown in some studies to reduce the incidence of complications as compared to Veress needle puncture access *(11)*. This is particularly true for the small abdominal cavity of infants.

Once the 12 mm camera port is in the peritoneum, we introduce a 30-degree up lens. This allows for visualization of the abdominal wall. Trocar placement must be done with patient twisting and pushing to get through the fascia in a controlled fashion. Another option is incision of the fascia and peritoneum and then introduction of the trocar with a blunt obturator.

For renal cases, we bring in an 8 mm upper midline port and an ipsilateral lower quadrant port. Care is taken to avoid the falciform ligament with the upper abdominal port. It is preferable to bring the port in on the ipsilateral side of the falciform ligament so that instruments do not needlessly pass through the falciform or damage it. We prefer to have our trocars at least one fist away from the camera port and do this at an approximately 120 degree angle from one another. We have found that it is helpful to place a 2-0 polyglactin curved GU needle into the fascia just after the skin incision for the trocar sites. This gives a counter-traction handle on the abdominal wall for trocar insertion and allows for easier closure of the fascia at the end of the procedure. Alternatively, the closure of the fascia can be done with the abdomen fully distended to more easily see the fascia. Visualizing the needle placement with the intra-abdominal camera will confirm that the needle passes through the peritoneum and therefore through the fascia. We make use of a 5 mm fourth arm accessory port brought in through the contralateral upper abdomen. Alternatively, one can use the fourth arm of the new version of the da Vinci surgical system (Intuitive Surgical, Inc. Sunnyvale, CA).

At this point, with all of the trocars in place, we bring the ipsilateral side of the table back up. This must be done prior to docking the robot. We have found that it is easier to accurately bring the patient to the robot than the robot to the patient. Rather than have the nurse drive the robot right or left, we unlock the table, and move the table so that the camera port is accurately lined up with the middle arm of the robot. The robot is then driven straight forward and stopped at a spot where we can maintain the sweet spot for the camera. The 30-degree up lens is reintroduced into the abdomen. It pays for the surgeon to remain scrubbed at this point in order to more easily facilitate introduction of the instruments into their proper position in the abdominal cavity.

At the beginning of the procedure both instruments should be capable of electro-coagulation. I test both of them against the lateral abdominal wall. One of our cases had an inadvertent injury to the bowel when there was a miscommunication between the nurses and doctors as to which instrument was "hot." It is also important to remind the assistant to bring their accessory

instruments into the operative field by aiming anteriorly and staying close to the anterior abdominal wall. This will hopefully avoid blind passage of instruments into bowel.

With commencement of the procedure it is best to remind oneself that greater use of clutching results in more facile hand and instrument movement. The more one clutches, the more likely it is that one's hands will be in the center of the console at a proper ergonomic position that allows for proper surgical maneuvers.

As described in the pyeloplasty chapter, often the renal pelvis is seen bulging through the mesentery, especially in a thin child. If that is the case, we prefer to incise the mesentery, and then access the UPJ in a trans-mesenteric fashion *(9,10)*. This obviates the need for mobilization of the colon. The trans-mesenteric approach can be done safely if care is taken to stay clear of the mesenteric vessels (Fig. 1). However, if the renal pelvis is not quite distended, or if the mesentery is dense, it pays to reflect the colon medially in order to expose the ureteropelvic junction. A traction suture is brought through the abdominal wall into the renal pelvis for a pyeloplasty and then this suture is brought back out through the abdominal wall and allows the surgeon to elevate the area of interest up and away from the other structures of the peritoneum *(12–14)*. This helps greatly with exposure. We have adapted to use an absorbable suture (i.e., polyglactin or chromic) so that if the running closure of the renal pelvis is short, it can be then tied to the absorbable traction suture already in place (Fig. 1).

When addressing a UPJ obstruction due to a crossing vessel, it is preferable to dissect the renal pelvis and the ureteropelvic junction as much as possible. This dissection will allow the UPJ to be pulled out from behind
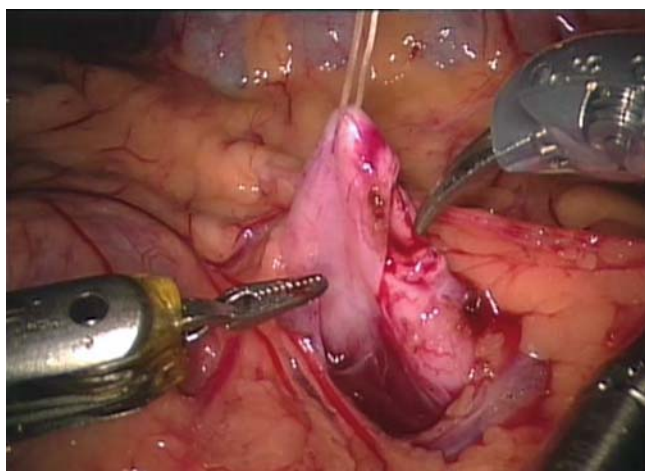
Fig. 1. Trans-mesenteric approach to the UPJ. The traction suture lifting the renal pelvis is absorbable.

the crossing vessel (Fig. 2). This is preferable to trying to introduce your instruments behind the vessel which may put a hole in the back wall of the vessel and cause significant bleeding. Once the UPJ is dissected to the point that it can pass freely to and fro behind the obstructing vessel, the pelvis can be transected.

Fig. 2. Ureteropelvic junction (UPJ) being brought out from behind a crossing vessel (V).

When the UPJ is adequately exposed, the pelvis is incised just below the traction suture and a diamond shape of renal pelvis is excised. This section of pelvis above the ureteropelvic junction can be used as a handle as it will be discarded *(14)*. The ureter is spatulated on its lateral surface with care to preserve the significant ureteral blood vessels. The anastomosis of the ureteral walls to the renal pelvis is then performed.

I have learned from our adult colleagues and their robotic prostatectomy procedures that it is helpful to do the anastomosis by introducing two separate sutures tied together at their back end. Typically this is a 4-0 or 5-0 poliglecaprone suture of two different colors. The back ends are tied and this is helpful in two regards. First of all, the knots do not need to be tied at the time of the anastomosis and secondly the two different colors allow for easy identification in running one side of the anastomosis versus the other. The first side of the anastomosis is done as a running suture with occasional locking of the suture. The second side is also a running suture and is begun after passing the needle behind the ureteropelvic junction. Near the end of the anastomosis a Double-J ureteral stent is brought in via the 5 mm accessory port and passed in an antegrade fashion *(10)*. There are those that prefer preoperative retrograde placement of a ureteral stent via cystoscopy *(13,15)*; however others feel this actually hinders intra-operative manipulation of the ureter. As mentioned prior, we bring this through the 5 mm accessory port with approximately 1 cm of wire extending beyond the stent. Just prior to

passing this stent into the bladder, the bladder is filled with methylene blue. The dye will reflux up the double-J stent, confirming the position of the stent in the bladder *(10)*. It is always better to opt for a longer stent as problems can arise if the stent is too short and migrates out of the renal pelvis into the ureter.

Tying knots in robotic procedures takes a bit of a different skill set than in open surgery *(16)*. The beginning of the knot tying is done from a wide angle view that allows visualization of the end of the suture. The end point for knot tying in open surgery is dictated by tactile feedback. In robotic surgery the end point is a visual one; as we lay the knot down, we zoom in, change the camera's focus and release the suture when we see the knot laying flat.

There are variable length double-J stents that measure 10–20 cm or 22–30 cm in the 4.7 French diameter. These stents have multiple coils at both ends that allow the stent to extend as necessary. However, it is important to be prepared for the possibility that the stent will not pass the ureterovesical junction. As in all manners of surgery, it is better to do things without force. If the stent does not pass, there are also smaller 3.7 French Double-J stents that exist for passage. Both robot arms are used to pass the stent and guidewire. Once the end of the Double-J stent is seen, the guide wire is removed, and the Double- J stent is placed in the renal pelvis. The methylene blue effluxing confirms its position. We then finish closing the renal pelvis. If the coil of the stent does not settle easily into the renal pelvis, it is because the pelvis is still too wide open and some more of the pelvis should be closed before reintroducing the coil. In the scenario of a crossing vessel causing UPJ obstruction, we transpose the new ureteropelvic junction anastomosis anterior to the vessel.

Toward the end of the procedure, usually when the needles are ready for removal, we often park the needles by placing them in the side abdominal wall, like a pin cushion.

At the end of the procedure, when all of the suturing is done, we straighten the needles with our laparoscopic instruments. In thin children, we can pass the needles directly out of the abdominal wall. This is done to avoid loss of the needle as can sometimes happen when removing the needle through a trocar. If the child is not thin enough, we will bring the needle out through the 8 mm trocar just as we brought it in through the 8 mm trocar. Removing needles through a 5 mm trocar increases the chance of loss of the needle and a great deal of wasted time looking for it in the abdomen. Some people close the mesentery overlying the UPJ if the procedure was done in a transmesenteric fashion although it is not absolutely necessary.

Nephroureterectomy is most often performed in a setting of high-grade reflux into a non-functioning kidney. When nephroureterectomy is performed the trocar position is somewhat different. The upper midline trocar is in the same place. However, it is helpful to move the lower abdominal trocar from the ipsilateral lower quadrant to at least the lower midline or even a bit onto the contralateral side of midline. When placing the lower midline

8 mm trocar, one must be absolutely sure of the location of the dome of the bladder and proceed slowly to avoid the bladder. This is particularly true in smaller infants where the working space is quite limited. In the nonfunctioning kidney, the renal pedicle vessels are usually smaller than normal. Vascular control can be achieved by suture, ENDO GIA stapler or the LigaSure device (Valleylab, Boulder, Colorado). All should be available in the operating room prior to the needed use. It is also worth considering pre-placing a suture into the abdominal cavity (and parking it in the abdominal wall) for quick access in case hemostasis needs to be achieved rapidly (Fig. 3). Suction/irrigation devices should be at the ready too. Although ideally it would be better to remove every last trace of ureter in a case of massive reflux leading to loss of renal function, we have left small stumps of approximately 2 cm and have seen no clinical consequence from this. A large 2-0 polyglactin needle is used to doubly suture ligate the distal stump.
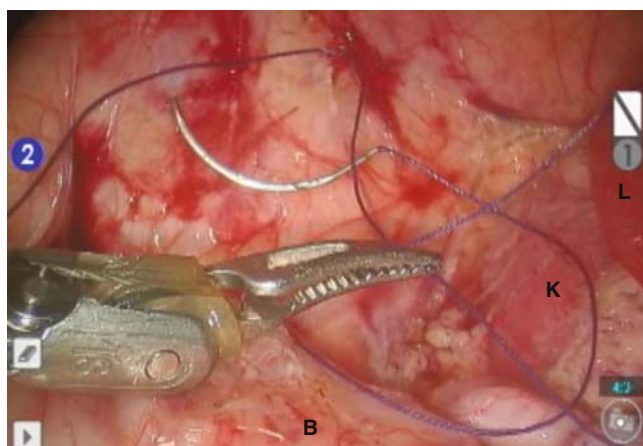
Fig. 3. Placement of a suture into the side wall of the abdomen allows for rapid access in the event of significant bleeding (*L* = liver; *K* = kidney; *B* = bowel).

We have also performed a robotic Malone Antegrade Continence Enema procedure (MACE) (Fig. 4). Initially we had the idea to use one of the instrument trocar sites for the creation of the stoma. However, we would not recommend that in the future. Using the same instrument trocar site for the stoma leads to awkward movement of the robot arm directly down onto the area of the surgery. At the end of mobilization of the appendix for the MACE procedure, the abdomen should be somewhat desufflated in order to allow for the appendix to reach the skin. With the abdomen fully inflated you can get a false, discouraging impression regarding the length of the appendix.

We have used the robot to perform a bilateral oophorectomy and hysterectomy in an intersex case. The procedure was done as in any other laparoscopic hysterectomy. However, since the robot is more facile than standard laparoscopy, and suturing the vaginal stump requires dexterity, we preferred
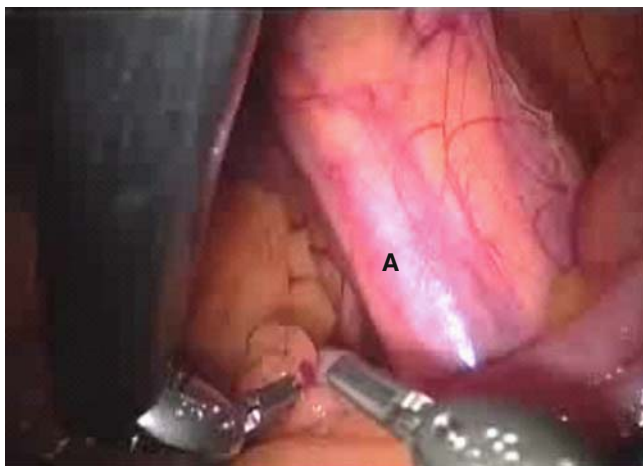
Fig. 4. MACE procedure with the appendix (A) and its mesentery exiting the abdominal wall.

to use the robot. We also used, in this case, the LigaSure device which allowed for sealing of vessels. One should be very careful as one works along the cervix and uterus to identify the significant vessels and ligate them with the LigaSure. As with other hysterectomies, one must be constantly mindful of the location of the ureters. Robotic Mullerian duct remnant removal has also been described.

In regard to upper pole nephrectomies, exposure is paramount. In order to gain that exposure, one must reflect the splenic or hepatic flexure of the colon. The upper pole ureter is transected and used as a handle as it is dissected in a cephalad direction toward the renal pedicle (Figs. 5, 6, 7). The
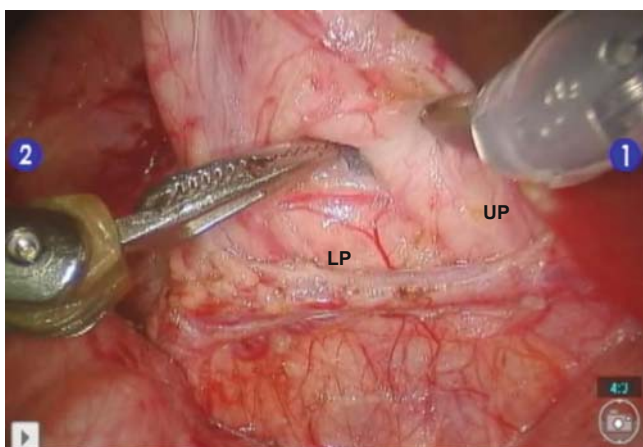
Fig. 5. This is a case of an ectopic upper pole ureter. The dilated upper pole ureter (UP) and normal lower pole ureter (LP) are clearly seen. Dissection is done as close to the upper pole ureter as possible.
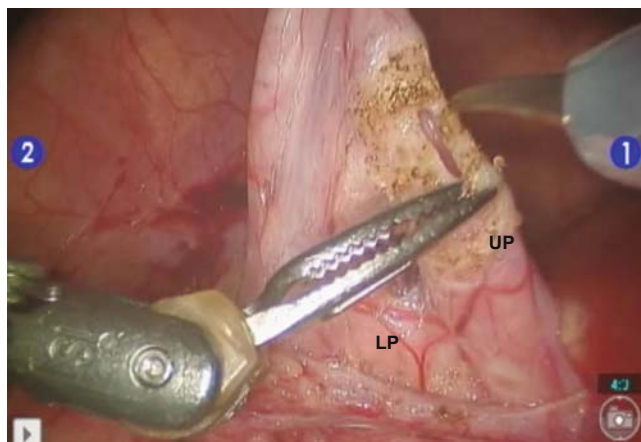
Fig. 6. The upper pole ureter (UP) is being transected while the lower pole ureter (LP) is kept in sight and safely away from the dissection.
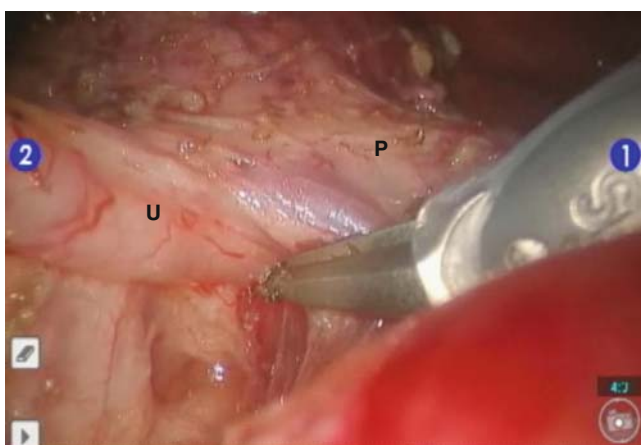
Fig. 7. Upper pole ureter (U) being used as a handle and guide to dissect in a cephalad direction towards the renal pedicle (P).

dissection should adhere to the wall of the upper pole ureter to avoid compromising the blood flow to the normal lower pole ureter. It is preferable to place the ureter on constant caudad traction and free the ureter from all adventitial attachments; this will allow for safer dissection as opposed to trying to dissect in the region of the renal pedicle. One can then grab the upper pole ureter from above and pull the freed ureter out from behind the renal pedicle. The ureter is now free from the pedicle and one has avoided placing instruments behind the main renal pedicle. The very small upper pole vessels to the dysplastic nonfunctioning upper pole of the kidney can be controlled with LigaSure (Figs. 8 and 9) and we in fact use the LigaSure to also come across the dysplastic tissue to aid in hemostasis.
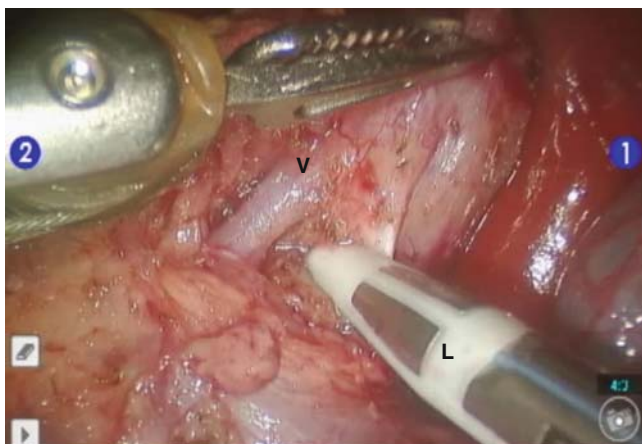
Fig. 8. Ligasure device (L) poised to seal a small upper pole vessel (V).
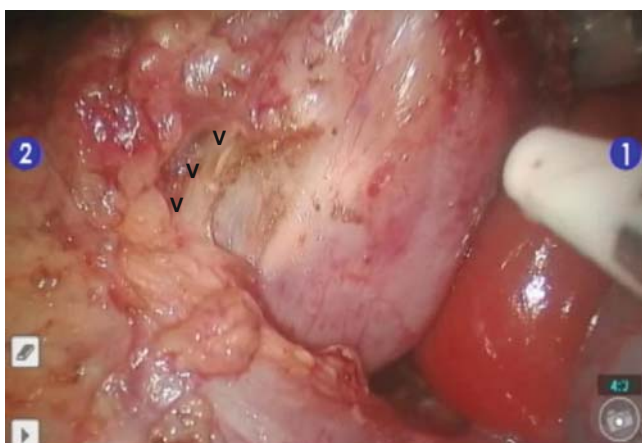
Fig. 9. The vein is now sealed and ready to be transected (seen just to the right of the Vs).

In children with UPJ obstruction and renal stones we and others *(17)* have used the robot for the concomitant performance of a pyeloplasty as well as nephrolithotomy. Prior to performing our pyeloplasty we make a small 1 cm incision in the renal pelvis approximately at the area where we would do our pelvic incision. We then bring a flexible cystoscope through the 5 mm port. Using our robots arms we feed the scope into the incision in the renal pelvis. Once inside the renal pelvis, the scope can be maneuvered and the large stones can be grasped and removed in their entirety or broken with laser lithotripsy. The pyeloplasty is then done in the standard fashion.

Successful endeavors, no matter what the field, share the trait of forethought and preparation. However, many successful people maximize their

success and experience by setting aside some time following their work to critically analyze what went well and what did not. Integrating the observations of all members of the team (nurses, residents, anesthesiologists, even family members) not only adds insight but also gives each team member a sense of importance and accomplishment. Committing these observations to writing is the best way to utilize these observations.

Finally, as has been said in many other settings, no one of us is as smart as all of us. The exchange of ideas via personal reading and research as well as by intellectual exchange at academic forums will not only lead to personal improvement but to the advance of the field of pediatric robotic surgery.

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8

Robot-Assisted Laparoscopic Pyeloplasty

Chad R. Tracy and Craig A. Peters

Abstract Laparoscopic pyeloplasty offers the success of open surgery with the benefit of decreased postoperative pain and decreased length of stay. Its use, however, is limited by the steep learning curve required for proficient laparoscopic skills. The introduction of robotic assistance shortens the laparoscopic learning curve and may allow increased use of laparoscopy in performing pediatric laparoscopic pyeloplasty. This chapter describes the key steps of robotic-assisted laparoscopic pyeloplasty including patient preparation, patient positioning, robotic set-up, use of a "hitch" stitch, antegrade and retrograde stent placement, ureteropelvic junction reconstruction, and postoperative care. In addition, the chapter includes a summary of current studies related to transperitoneal and retroperitoneal robotic-assisted laparoscopic pyeloplasty.

Since its introduction in 1949, the Anderson-Haynes dismembered pyeloplasty has become the gold standard in the management of ureteropelvic junction (UPJ) obstruction, with success rates greater than 90% *(1)*. While surgery for UPJ obstruction has traditionally been through an open approach, laparoscopic pyeloplasty has gained acceptance in children since its first report in 1995 *(2)*. Several authors have demonstrated the feasibility of laparoscopic pyeloplasty in children with similar success rates compared to open surgery, but with decreased postoperative pain requirements and decreased length of stay *(3–9)*. Initially the laparoscopic approach was primarily limited to older children, but recent evidence has supported its use in infants and children less than 2 years of age *(10,11)*.

Due to the steep learning curve required for performing reconstructive laparoscopy, particularly intracorporeal suturing, many pediatric urologists have been reluctant to undertake laparoscopic pyeloplasty. Development of robotic assistance using the daVinci Surgical system (Intuitive Surgical, Sunnyvale, CA) allows for the potential to overcome many of the difficulties encountered in pediatric laparoscopic surgery. In particular, robot assistance has the ability to increase surgical precision and enhance the technical skills necessary for performing complex reconstructive surgery through its use of 3D visualization, improved instrument articulation, tremor filtering, and variable scaling.

1. TRANSPERITONEAL TECHNIQUE

1.1. General Patient Preparation

All patients and their family are consented preoperatively regarding the risks of surgery including the possibility of conversion to open surgery. In addition, all family members should understand that the surgeon will perform the surgery and that the "robot" acts as an instrument in a "master–slave" configuration. During preoperative counseling, patients and families are allowed to make the decision on whether they would prefer a ureteral stent with a string through the meatus for easy extraction, or whether they would prefer cystoscopic removal of their stent, often requiring a brief anesthetic. Patients are placed on a clear liquid diet 24 hours prior to the procedure and are given a single Dulcolax suppository the night before the surgery in order to decrease the bulk of stool in the colon and facilitate the transperitoneal approach. Because of the minimally invasive nature of laparoscopic surgery, we do not place preoperative epidural catheters or caudal anesthetics for pain control.

1.2. Patient Positioning and Robot Set-up

If the patient and family have chosen to have a ureteral stent with extraction string, the patient is initially placed in the dorsal lithotomy position. Cystoscopy with retrograde pyelography is performed based on surgeon preference and then an appropriate length ureteral stent is placed over a guidewire and coiled at the level of the UPJ. Placement directly at the UPJ prevents decompression of the pelvis and enhances identification of the pelvis/UPJ obstruction during laparoscopy. The extraction string is then shortened and fixed to the patient's thigh with adhesive tape.

After placement of a Foley catheter for bladder drainage, the patient is placed over a wedge cushion or jelly-roll with the affected side elevated 30–45 degrees. The patient is carefully padded with their arms at their sides to allow more positional flexibility when docking the robot. The patient is then strapped to the table using 2-in. cloth tape and the table is "test-rolled" to confirm that the patient is appropriately stabilized on the table (Fig. 1).

Fig. 1. The patient is positioned with the affected side elevated 30–45 degree and securely fastened to the table. The table is rotated to place the patient supine for port placement and then counter-rotated to optimize exposure of the kidney prior to docking the robot.

Peritoneal access is obtained through a modified open Hasson technique utilizing a 12-mm umbilical incision and preplaced fascial sutures. The abdomen is then insufflated with CO_2 to a maximum pressure of 12 mmHg. The 30 degree daVinci endoscope is introduced and laparoscopy is performed to evaluate patient anatomy and confirm the absence of any adhesions to the abdominal wall in the expected location of the other trocars. Two robotic ports sites are chosen, with one in the midline between the umbilicus and xyphoid and the second in the mid-clavicular line 2–4 cm below the umbilicus (Fig. 2). In smaller children or in those with a large renal pelvis projecting into the lower retroperitoneum, the inferior trocar should be placed more medially and inferiorly in order to maximize the working space. After choosing the port site, the skin and subcutaneous tissues are incised down to fascia and a box stitch is preplaced for later closure of the fascia. The robotic cannulae (5 or 8 mm) are placed under direct visualization using

Fig. 2. The 12 mm camera port is placed at the umbilicus and the two robotic ports (5 or 8 mm) are placed in the midline between the umbilicus and xyphoid and in the mid-clavicular line 2–4 cm below the umbilicus.

dilating obturators. Because of the added bulk, the cone-shaped Hasson cannula is not utilized in children, but a snug fit is ensured by the preplaced fascial suture.

After placement of the robotic trocars, the abdomen is carefully inspected for any bleeding or inadvertent injuries during port placement. While directly visualizing the renal pelvis, the table is tilted by raising the affected side until the bowels are medially displaced. The daVinci robot system is brought over the ipsilateral shoulder in order to align the axis of the camera and robot with the UPJ prior to engaging the robotic arms. Dissection is initially carried out using the hook cautery (5 mm) or hot scissors (8 mm) in the surgeon's dominant hand and the Maryland or DaBakey forceps in the contralateral hand.

2. TRANSMESENTERIC APPROACH

Infants and thin children often have little fat in their mesentery, which can allow for rapid identification of the UPJ and facilitate a transmesenteric

approach on the left. The transmesenteric approach is preferable as it allows for minimal tissue disruption, decreased dissection of the bowel, and faster access to the UPJ. If using the transmesenteric approach, the patient should not be too steeply positioned in the flank position as this may cause the left colon to drape over the surgical site. Once the UPJ is identified, the peritoneum (mesentery) is incised over the region and the proximal ureter and pelvis are mobilized through the mesenteric window (Fig. 3A).
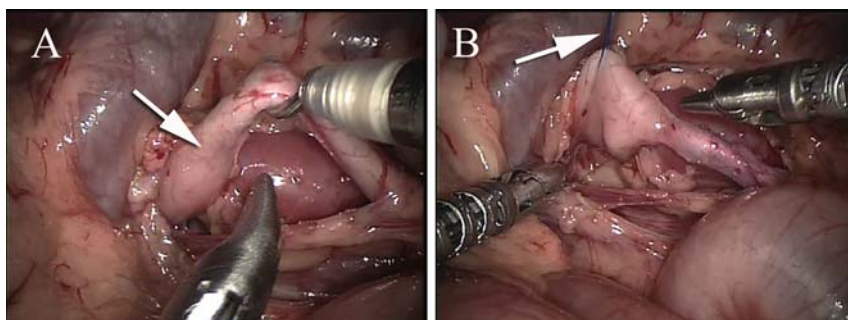
Fig. 3. (**A**) Limited mesenteric fat in children allows for transmesenteric access to the UPJ (*arrow*). (**B**) The "hitch" stitch (*arrow*) is passed through the abdominal wall to increase exposure by lifting the pelvis away from the bowel and any bleeding or urine in the surgical field.

3. RETROCOLIC APPROACH

In older children, heavier children, and most children with a right-sided UPJ obstruction, it is necessary to use a retrocolic approach. The ascending (right) or descending (left) colon is mobilized from the flexure down toward the iliac vessels until the bowel can be retracted medially enough to expose the UPJ. Once the UPJ is exposed, the proximal ureter and UPJ are carefully mobilized to facilitate dismembered pyeloplasty. With appropriate port placement during the initial portion of the surgery, we have not found it necessary to utilize standard laparoscopic instruments during this portion of the procedure.

3.1. Hitch Stitch

Once the UPJ has been mobilized, a "hitch" stitch is placed in the renal pelvis in order to retract and expose the renal pelvis (Fig. 3B). Early placement of a "hitch" stitch facilitates dissection of the pelvis and anastomotic repair by providing stabilization and increasing exposure by lifting the pelvis away from the bowel and any bleeding that may be obstructing a clear view. In younger children and thinner patients, the retraction stitch can typically be passed directly through the abdominal wall using a 3-0 or 4-0 PDS. The tail of the suture is held on the outside by the bedside surgeon while the

needle is passed through the renal pelvis and back through the abdominal wall. The tension can then be controlled from the outside by pulling up on both ends of the suture.

In larger patients it is often difficult to pass the needle directly through the abdominal wall and it must be passed through one of the 8 mm ports. The pelvis is sewn up to the abdominal wall with the appropriate tension using a 3-0 or 4-0 vicryl suture, which prevents slipping of the knot while tying to the posterior peritoneum. Completion of this knot may be facilitated by having the bedside assistant press down on the abdominal wall to decrease tension on the suture. Since there is no outside control of the knot, this technique does not allow for fine adjustments in tension during the procedure.

3.2. UPJ Excision, Spatulation, and Ureteral Transposition

The dilated renal pelvis is incised and transected above the level of the UPJ, leaving a segment of the pelvis on the proximal ureter to act as a "handle" and prevent manipulation of the ureter (Fig. 4). By using the ureteral "handle," the ureter is spatulated for 1.5–2 cm along its lateral aspect until healthy tissue is encountered (Fig. 5). If there is a crossing vessel identified during initial dissection, the ureter should be transposed to the anterior surface of the vessel before performing the anastamosis. Limited resection of the renal pelvis by surgeon preference can certainly be performed at this point, though care should be taken to avoid over-excision.
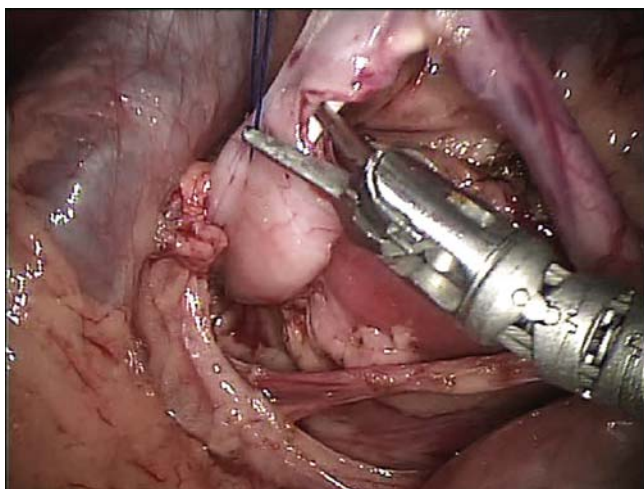
Fig. 4. The renal pelvis is incised leaving a portion of pelvis on the ureter to act as a "handle" for later ureteral manipulation.

3.3. Reconstruction

The anastomosis can be performed using running or interrupted 4-0, 5-0, 6-0, or 7-0 absorbable monofilament sutures depending on the patient's age.
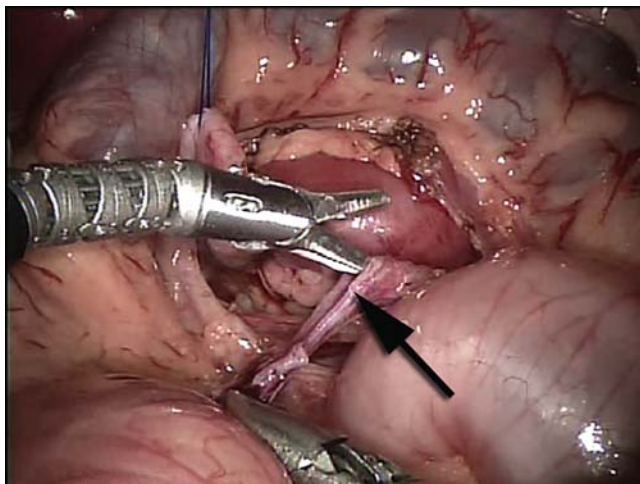
Fig. 5. The ureter (*arrow*) is spatulated distal to the UPJ for a distance of 1.5–2 cm along its lateral boarder.

We prefer running sutures as they decrease the time required for performing the anastomosis and do not require the frequent changing of instruments required for cutting the anastomotic stitch. Stitches should be cut to 12–14 cm depending on patient's age in order to allow sufficient length for the anastamosis without a cumbersome excess of suture. The anastomosis is started at the vertex of the ureteral spatulation (Fig. 6) and run up the posterior side of the ureteral-renal pelvis junction until reaching the stenotic
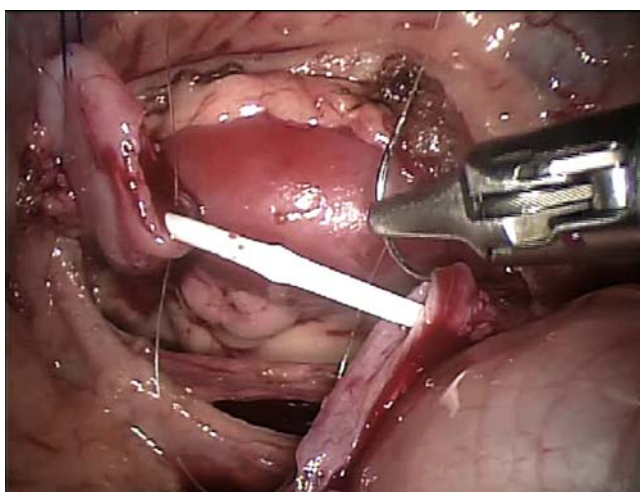
Fig. 6. The initial anastomotic stitch is placed between the vertex of the ureteral spatulation and the inferior portion of the pyelotomy.
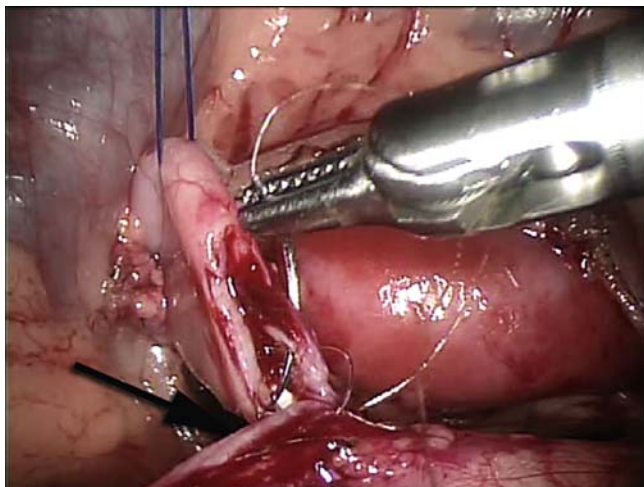
Fig. 7. The back wall of the anastomosis between the pelvis and the ureter (*arrow*) is completed prior to placing the antegrade stent.

portion of the ureter (Fig. 7). Once this portion of the anastomosis is complete, the remnant of renal pelvis and the stenotic UPJ should be excised and removed out one of the robotic ports. Alternatively, if the segment is too large to remove out one of the ports, it may be placed off to the side and removed at the end of the case using a laparoscopic grasper and pulling the specimen out one of the port sites.

3.4. Stent Positioning

After completing the posterior anastomosis, the stent coil is placed into the pelvis prior to performing the anterior closure. If the patient and family elected to have no extraction string on their ureteral stent, the stent is placed in an antegrade fashion at this time (Fig. 8). A 16-gauge angiocatheter is passed under direct visualization below the costal margin and, after removal of the needle, a 0.28 or 0.35 mm wire is passed through the catheter lumen and guided into the proximal ureter and down to the bladder. It is important to only grasp the wire with one arm of the robot at a time during passage as excessive manipulation can lead to fraying of the wire. An appropriate length double-J ureteral stent is passed over the top of the wire and down to the bladder until the proximal coil can be placed within the renal pelvis. Reflux up the ureteral stent of methylene blue inserted in the Foley catheter can confirm placement of the stent within the bladder.

Once the stent has been inserted, the anastomosis is completed with a running suture up the anterior surface of the ureteral-renal pelvis anastomosis (Fig. 9). Depending on the size of renal pelvis initially excised, further sutures may be required to close any remaining opening within the renal
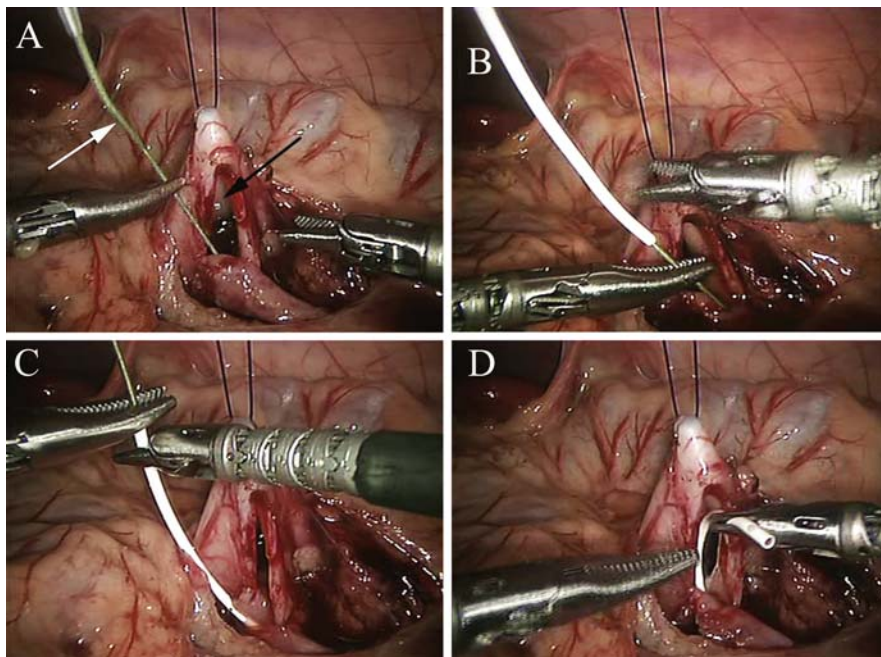
Fig. 8. (**A**) A 16G angiocatheter is inserted through the abdominal wall and used to place a PTFE wire into the ureter (*white arrow*), distal to the open renal pelvis (*black arrow*). (**B**) An appropriate length ureteral stent is placed over the wire down to the bladder. (**C**) The wire is removed and the stent coil (**D**) is placed into the pelvis prior to anastomosing the anterior wall.
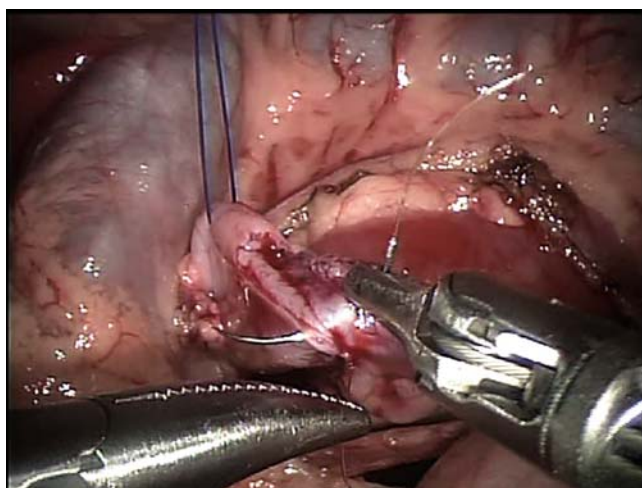
Fig. 9. The anastomosis is completed with a running suture after placement of a double-J ureteral stent.

pelvis. If there is a defect within the peritoneum over the UPJ, it may be closed over the top of the repair using chromic or vicryl sutures. Drainage of the renal pelvis is done by way of the ureteral stent and, therefore, we do not routinely place a wound drain.

At the completion of the repair, spilled urine or blood should be aspirated from the field and lateral gutters. The trocars are removed under direct visualization and the robot is disengaged. Port sites are closed with previously placed box stitches and the incisions are closed with 4-0 or 5-0 vicryl.

4. RETROPERITONEAL RALP

Open pyeloplasty in children is most often performed via a retroperitoneal approach, which has led some authors to advocate retroperitoneoscopic pyeloplasty. While this approach was first described in children by Yeung et al. in 2001 using standard laparoscopy *(12)*, it has since been modified by Olsen and colleagues using robotic assistance *(13,14)*. While there are many similarities between the surgeries, the differences are described below.

Patients are placed into the 90–100 degree flank position with the affected side upward. A small amount of flex is obtained by placing a gel roll beneath the contralateral hip and the patient is secured in place. A 15 mm incision is made above the iliac crest in the anterior axillary line. The retroperitoneal space is initially defined with blunt finger dissection and then a 100–300 ml balloon trocar is placed for formal dilation of the retroperitoneal space. After leaving the balloon inflated for 5 minutes, the dilator is removed and the remaining instruments are placed under direct palpation to avoid injury to the peritoneum. The lateral 5 or 8 mm robotic port is placed at the lateral aspect of the latissimus dorsi muscle two fingerbreadths above the iliac crest. The medial robotic port is placed beneath the costal margin at the anterior axillary line. An optional assistant port (5 mm) is placed in the iliac fossa for assistance with suctioning, cutting, and retraction. A 12 mm balloon-tipped port is then placed into the original incision and the excess fascial opening is closed with 2-0 vicryl sutures. Use of a balloon-tipped port helps maintain pneumoperitoneum and decreases the risk of subcutaneous emphysema.

Once the ports have been placed, the robot is docked over the ipsilateral shoulder at 45–60 degrees and a scissor or hook cautery is placed in the dominant hand and a Maryland forceps or DeBakey grasper is placed in the contralateral hand. Gerota's fascia is incised and the UPJ is dissected free into the field. Complete dissection of the lower pole of the kidney is essential in order to identify a crossing vessel. Failure to identify a vessel during this portion of the procedure has led to failure of UPJ reconstruction *(14,15)*.

After the UPJ has been dissected free, a holding stitch is placed distal to the UPJ obstruction on the proximal ureter and a second holding stitch is placed in the renal pelvis proximal to the UPJ obstruction. The remain-

der of the case is carried out similar to the transperitoneal approach with dismembering of the UPJ, ureteral spatulation, and reconstruction over a double-J ureteral stent. As with the transperitoneal procedure, ureteral stents may be placed prior to pyeloplasty using cystoscopy or percutaneously during the case depending on patient and parental preference.

5. Y-V PLASTY

In patients with excessive scarring of the UPJ, mobilization of the renal pelvis may be difficult and consideration should be given to performing a Y-V plasty rather than a traditional dismembered pyeloplasty *(16)*. After freeing the anterior surface of the renal pelvis and exposing the UPJ, a Y-shaped incising is made with the stalk of the Y extending through the stenotic UPJ. Once the stent has been placed into the pelvis, the defect is closed by advancing a V-flap across the defect to the vertex of the incised proximal ureter. If limited mobility hinders closure, interrupted sutures may be preferred over a running suture line.

6. POSTOPERATIVE CARE

Following surgery, patients are given a regular diet as tolerated and transitioned to oral pain medications. The Foley catheter is typically removed the morning after surgery and >90% of patients are discharged home in the morning of postoperative day 1. Patients with an extraction string return for stent removal in 2 weeks, whereas those without a string follow-up in 4 weeks to have their stent removed under a light anesthetic. An ultrasound is performed one month following stent removal with further imaging dictated by ultrasound findings and clinical course.

7. RESULTS

The initial experience with robotic-assisted pediatric laparoscopic pyeloplasty is promising (Table 1). Lee et al. reported an initial series of RALP vs. open pyeloplasty in 33 age-matched children between 0.2 and 19 years (mean 7.8) *(15)*. Children undergoing RALP had a significantly shorter length of stay (LOS) (2.3 vs. 3.5 days) and required significantly less narcotics for pain control. Faster operative times were found in the open cohort compared to the robotic cohort (181 vs. 219 minutes), though with increasing experience using RALP, operative times approached those of open surgery. At 10 months of follow-up 31/33 patients in the RALP cohort had resolution of their UPJ obstruction by renal ultrasound or diuretic renogram. One patient required re-operation for persistent UPJO because of a missed crossing vessel during a retroperitoneal approach and one patient was lost to follow-up.

Table 1
Results of Pediatric Robot-Assisted Laparoscopic Pyeloplasty Using the daVinci Surgical System

	# Pts	Approach	Age (years)	OT (mins)	LOS (days)	F/U (months)	Success*
Lee (15)	33	TP	7.8	219 (123–308)	2.3 (0.5–6)	10	96%[†]
Yee (18)	8	TP	11.5	363 (255–522)	2.4 (1–5)	14	100%
Franco (19)	15	TP	11.9	223 (150–290)	2.3 (2–7)	11.5	100%
Olsen (14)	65	RP	7.9	143 (93–300)	2 (1–6)	12	94%
Kutikov (20)	9	TP	0.47	122 (N/A)	1.4 (N/A)	18	100%
Atug (21)	7	TP	12	184 (165–204)	1.2 (1.3)	10	100%[†]

*Defined as decreased hydronephrosis on renal ultrasound and/or improved drainage on radionuclide imaging.

[†] Excludes one patient from each group who was lost to follow-up

LOS – Length of stay; OT – Operative time

Success with retroperitoneal RALP has also been reported (14). A recent series of 65 children with an average age of 7.9 years (1.7–17.1) reported on an operative time of 143 minutes (range 93–300) and a mean hospital stay of 2 days (range 1–6). One patient required open conversion because of small working space and four required nephrostomy tube placement, of which two were unstented and two had ureteral obstruction from blood clots. At a mean follow-up of 12 months, four patients (6%) required repeat surgery because of ureteral kinking (2), decreasing differential function on renography (1) and an overlooked lower pole vessel (1).

While the benefits of RALP are emerging for primary repair of UPJO, its use has also been reported for reoperative pyeloplasty in children who have failed open pyeloplasty (17). Robotically assisted reoperative pyeloplasty appears equivalent to its open counterpart in regard to success and improved over open surgery in regard to operative stay and postoperative pain.

8. CONCLUSIONS

Pediatric RALP appears to offer all of the advantages of open surgery along with the benefits of laparoscopy including shorter hospital stay and decreased postoperative pain. With increasing surgical experience, operative times appear to approach those of open surgery. While the significant cost of the daVinci surgical system may initially limit the broad application of RALP, its ease of use over conventional laparoscopy will likely allow increased utilization of laparoscopic pyeloplasty in children.

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9

Robotically Assisted Laparoscopic Nephrectomy and Adrenalectomy

Arun K. Srinivasan and Lane S. Palmer

Abstract Robotic nephrectomy is not a common procedure in children. However, when it is performed, the sequence of steps is those used in adults. Fortunately, the indications for nephrectomy or nephroureterectomy are typically for benign disease and the non-functioning kidney rather than for malignancy. In this chapter, we aim to provide the reader with an understanding of performing robotic nephrectomy, nephroureterectomy, and adrenalectomy.

Keywords Kidney · Robotic · Laparoscopy · Urology · Children · Nephrectomy

1. INTRODUCTION

The concept of minimal invasive surgery in medicine was getting popularized in the 1980s and the first laparoscopic upper tract urologic procedure was a laparoscopic nephrectomy reported in 1991 by Clayman et al. *(1)*. The first pediatric laparoscopic nephrectomy was reported by Kavoussi et al. in 1993 *(2)*. Since this time, multiple reports have been published on laparoscopic nephrectomy in children. Some of the largest series of laparoscopic nephrectomy *(3–6)* reported hospital stay of 2 days or less, low incidence of complications and a "conversion to open surgery" rate of less than 5%. With these reports, indications for using laparoscopy in children and age range of children suitable for laparoscopy broadened. Reports of post chemotherapy Wilms tumor laparoscopic nephrectomy *(7)* and laparoscopic nephrectomy in children less than 1 year old were published *(8)* and laparoscopic nephrectomy was fast becoming an established treatment in children.

Limitations to laparoscopic surgery include two-dimensional vision, restricted degree of freedom, counter intuitive direction of movement (surgeon's hand movement in the opposite direction of movement of the tip of the instrument), and a prolonged learning curve. During this time there were accelerated advances made in computer-aided tele-metrics, high-definition imaging, and 3D technology that lead to the development of tele-manipulator system (Computer Motion) *(9)* and the first procedure using this technology was demonstrated in a porcine animal model *(10)*. Laparoscopic surgery in one sense paved the path to robotic surgery in urology and robotic-assisted laparoscopic surgery was the next logical step. The first report of robotic nephrectomy in humans was by Guillonneau et al. in 2001 on a 77-year-old woman with chronically non-functioning kidney secondary to ureteropelvic junction obstruction.

Present day robotic devices aid surgeons with high-resolution three-dimensional images, seven degrees of freedom of the instruments resulting in wrist-like maneuverability and tremor filtered instrument control. These are the main advantages that make the robotic assistance more valuable in the pediatric group of patients in whom renal surgery involves dissection around delicate and vulnerable structures that requires high precision in movement *(11)*. Robotics also permit a wider surgeon pool to offer minimally invasive pediatric renal surgery since the learning curve for robotic surgery is not as protracted as the learning curve associated with laparoscopy *(11)*. Robotic nephrectomy might be the simplest procedure to perform in a pediatric patient and hence serve as a valuable stepping stone, in terms of learning experience for the surgeon, to use the robot in more complicated procedures.

2. INSTRUMENTATION

The existing FDA approved robotic surgical system is the da Vinci system (Intuitive Surgical, Mountain View, California) that is used for multi-various urological procedures, both extirpative and reconstructive, in children. Traditionally, robotic instruments needed a 12 mm port for the three-dimensional dual channel camera and 8 mm ports for the working arms. As more and more pediatric patients underwent robotic surgery, instrumentation has gradually adapted to suit them better. A 5 mm "snake wrist" design working arm with seven degrees of freedom has been introduced to be used in pediatric patients. Although it uses a smaller port, the work space it may need might still be a limitation *(12)*. A new two-dimensional 5 mm endoscope has also been designed for use with robotic system in children. These improvements and further changes in future will aid further growth of robotic surgery in pediatric urology. Besides the before mentioned attributes of the da Vinci system, the specific virtues that aid better pediatric procedures are the motions scaling and magnification. Pediatric operative field and structures involved are small and delicate. Magnification obviously helps in

visualizing the structures better. Motion scaling means that the robot arm moves less than the arm of the surgeon on the console and this is traditionally set at 1:3 ratio. Hence for a 3 cm movement of the surgeon there is only a centimeter movement on the tip of the instrument. Coupling these with tremor control and three-dimensional imaging makes the robot an ideal operative tool in children with gentle and delicate dissection of the hilum and needle drivers that can use 7-0 sutures for any repairs.

3. INDICATIONS

The indications for performing nephrectomy in children can be grouped as benign and malignant conditions. The indications are not any different from open or traditional laparoscopic nephrectomy. There are no established reasons for performing robotic nephrectomy preferentially in a given patient other than surgeon and patient choice of procedure. Recent literature evidence on the most common reasons for performing pediatric nephrectomies are summarized as follows *(13)*:

Benign	
Multicystic dysplastic kidney (MCDK)	31%
Vesico-ureteral reflux	16%
Uretero-pelvic junction obstruction	6%
Medical/trauma/other benign	15%
Neoplastic	
Wilms tumor	19%
Other neoplasms	4%

4. ANATOMY

4.1. Adrenal Glands

The two adrenal glands reside in the intermediate pararenal compartment of the retroperitoneum. Each of the adrenal glands is surrounded by Gerota's fascia and is also separated from the upper pole of the ipsilateral kidney by a thin layer of connective tissue. Each adrenal weighs about 5–7 g and measures 3–5 cm in greatest transverse dimension. Their distinct yellow–orange color differentiates them from the surrounding adipose tissue. The right adrenal gland is pyramidal in shape and is positioned more superiorly. It is positioned superior to the upper pole of the right kidney, medial and posterior to the liver, lateral and posterior to the duodenum, and lateral to the vena cava. The left adrenal gland has a crescenteric shape and lies medial to

the upper pole of the left kidney. The splenic vessels, tail of the pancreas and stomach are all located anterior and superiorly to the left adrenal gland.

The vascular supply of the adrenal gland comes from three sources while it has a single venous drainage. The superior blood supply is derived from the aorta as the inferior phrenic artery. The middle blood supply is also derived from branches of the aorta. The most inferior blood supply comes from the ipsilateral renal artery. Each adrenal gland is drained by a single adrenal vein. The right adrenal vein empties directly into the posterior-lateral aspect of the vena cava. The left adrenal vein is joined by the inferior phrenic vein and together enters the left renal vein superiorly opposite the gonadal vein. The adrenal glands send lymphatic drainage into the para-aortic lymph nodes via lymphatics that parallel the venous drainage.

4.2. Kidney

Gerota's fascia surrounds each kidney superiorly, medially, and laterally. This fascia consists of a flimsy anterior layer that is closely associated to the peritoneum and a posterior layer that is distinctly tougher. The retroperitoneum can be separated into three compartments by these anterior and posterior layers of renal fascia. On the right side, the anterior pararenal compartment contains the ascending colon and duodenum while on the left side it contains the descending colon and pancreas. The intermediate pararenal compartment contains the adrenal glands, kidneys, perirenal fat, and the proximal ureter. The posterior pararenal compartment consists of adipose tissue. The anterior space is unique as it extends from one side of the abdominal cavity to the other. The pararenal fat is a separate layer of adipose tissue that surrounds Gerota's fascia anteriorly and posteriorly.

Understanding the topographical relationship between the kidneys and their neighbors helps the robotic surgeon during the initial portion of the surgery as well as during times of more difficult dissection. The topography that is common to the two kidneys includes (1) medially, the lower two-thirds of each kidney lay on the psoas medially, and (2) laterally, the kidneys encounter the quadratus lumborum and the transversus abdominis aponeurosis.

The right kidney is positioned lower than the left kidney and is crossed by the 12th rib. Superiorly, the upper pole lies adjacent to the liver; the peritoneum separates the kidney from the liver. The hepatorenal ligament is an extension of parietal peritoneum that connects the posterior portion of the liver to the superior pole of the right kidney. The descending portion of the duodenum lies anterior to the renal vein and the vena cava and is positioned close to the renal hilum and the medial aspect of the kidney.

The left kidney is positioned higher than the right kidney and is crossed by the 11th and 12th ribs. The spleen lies adjacent to the upper pole of the left kidney while the splenic flexure and descending colon lay anterolaterally.

The tail of the pancreas lies superiorly making injury a possibility. The splenic artery and vein lie adjacent to the upper pole of the kidney and hilum.

4.3. Renal Vessels

Bilaterally the renal arteries branch off the aorta at the level of L2 vertebrae just below superior mesenteric artery. The right renal artery courses behind the IVC and the left renal artery exits the aorta in a direct lateral course toward the left kidney. The renal artery branches into five segmental arteries and the first branch, most commonly, is the posterior segmental artery which branches prior to the hilum. This is important to note in preoperative imaging since early branching particularly on the right side means there are two significant arterial branches to ligate and divide at the renal hilar level.

The renal vein courses anterior and superior to the renal arteries. The right renal vein is typically short, non-branching and enters the inferior vena cava. The left renal vein is longer coursing anterior to the surface of the aorta and entering the left kidney. Left gonadal vein and the left adrenal vein joins the left renal vein in that order from lateral to medial before it joins the IVC. During surgical dissection, identification of the gonadal vein on the left side and following them cephalad will lead to the left renal vein and the right side lead to the inferior vene cava.

The size of the renal vessels may vary based on the age of the patient, the pathology, and the number of vessels. Smaller children obviously have smaller sized vessels. Multi-cystic dysplastic kidneys or other atretic kidneys may only have atretic vasculature. If the size of the vessel seem disproportionate to the size of the kidney or the age of the child, it should alert the surgeon of a possibility of either a polar vessel or an early division and hence prompt attempts to visualize the missing vessel with careful dissection around the hilum.

4.4. Ureters

The ureters are located posterior to the renal vessels. During nephrectomy or nephroureterectomy, the ureters are visible after mobilization of the colon is performed and the psoas major muscle is exposed. The ureters course along the anterior border of the psoas as they descend toward the bladder. The ureters run in close vicinity to the ascending colon on the right and descending colon on the left side. The gonadal veins, which run alongside each ureter, drain directly into the left renal vein on the left side and directly into the vena cava on the right side. The ureters are located posterior and lateral to the gonadal veins. The gonadal vessels cross the ureters anteriorly about a third of the way to the bladder. When the identity of the gonadal vein and ureter is in doubt, remembering this relationship and demonstrating peristalsis should make identifying the ureter clear. The ureter enters the bony pelvis as it crosses over anterior to the bifurcation of the common iliac

into the internal and external iliac arteries. In boys, the distal one-third of the ureter courses under the vas deferens. In girls, the ureters run posteriorly through the ovarian fossa traveling lateral to the cervix and underneath the broad ligament. Before the ureter enters into the bladder, it runs under the uterine artery (water under the bridge).

It is important during nephroureterectomy to keep in mind that the blood supply to the ureter varies as it descends toward the bladder. The upper portion of the ureter is supplied by branches of the renal artery, abdominal aorta, gonadal artery, and common iliac artery; these branches all enter the ureter medially. The distal ureters in girls are derived from the vesical, uterine, and middle rectal and vaginal arteries (all branches of the internal iliac artery). In boys, the distal ureter is supplied from branches of the aorta, gonadal artery, common and internal iliac arteries. The tributaries to the distal ureters enter them from the lateral approach. Once the arterial vessels reach the ureter they anastomose in a plexus that runs longitudinally within the adventitia of the ureter. The venous drainage of the ureter runs parallel to its arterial supply.

5. TECHNIQUE

Robotic nephrectomies in children can be performed both by a transperitoneal approach *(11)* and a lateral or flank or retroperitoneal approach *(14)*. The transperitoneal technique is more often utilized since there is more room for the instruments for adequate mobility and we prefer this approach. The overall technique for robotic nephrectomy in children has been adapted from the one described for adults. The significant concepts that differ in children are less working space, proximity of vital structures to each other and delicate nature of the dissection. The technique of robotic nephrectomy has been described by multiple authors *(11,14,15)*.

5.1. Patient Position

Positioning the patient optimally is of paramount importance for adequate visualization that aids a safe and smooth procedure. Positioning of the patient depends on the age of the patient. Adolescent or well-built younger patients are positioned in modified lateral decubitus position with a bump under the upper half of the abdomen which makes a 45 degree angle to the horizontal plane. Their ipsilateral arm is folded on their chest and the contralateral arm is left at a 90 degree angle to the body. The patient is strapped in this position with well-padded support to all pressure points to the operating table. The table is then tilted 60 degrees to the contralateral side to make intrabdominal contents to fall away from the operative area and also helps the colon to fall away from the kidney once it is mobilized. In babies, a smaller support is used to lift the operative side flank but the arms are left on the sides of the patient. The baby is secured well in this position to the

operating table and the table is turned to the contralateral side as described above. The ports are placed before turning the table and robot is docked on the ports after adequately airplaning the table to the contralateral side. Neither the table nor the patient should be moved after the robot has been docked.

5.2. Port Placement

Placement of the ports for the robot again depends on the size of the patient and space available. As in laparoscopy, the theory of triangulation is vital to ensure adequate room for maneuverability for the instruments without hitting on each other. As described by Peters, the traditional four-finger breadth space between port sites is not possible and hence it is vital for the surgeon to envisage the operative field and plan port placement accordingly.

Routinely, we place the 12 mm camera port in the umbilicus where even a centimeter size incision can be effectively made part of the umbilical cicatrix and hence made not visible. The working arm ports are placed on either side of the camera: one port placed subxiphoid in the midline and the other port placed in the ipsilateral lateral abdominal at or just below the level of the umbilicus in the mid clavicular line. Veress needle access is achieved to establish pneumoperitoneum and the camera port is placed first. A quick scan of the abdomen is then performed to confirm normal anatomy. The working arm ports are then placed as previously mentioned under direct vision. The instruments are then introduced and positioned under vision to prevent accidental damage to other intra-abdominal viscera. A fourth arm is placed when needed either in the midline below the umbilicus to fall midway between the camera and the working arm port or any such place to aid the bedside assistant to use suction or provide traction as might be needed.

6. OPERATIVE TECHNIQUE: ADRENALECTOMY

The adrenal glands can be approached by either a retroperitoneal or transperitoneal approach; however, since transperitoneal robotic surgery is currently favored, we will limit our discussion to this approach. In the transperitoneal approach to the left adrenal gland, the descending colon is medially reflected exposing the left kidney and renal hilum. Division of the splenorenal ligament and lateral peritoneal attachments allows the spleen to fall away. The tail of the pancreas must be identified anterior and medial to the kidney and adrenal gland. The plane between the tail of the pancreas and the left adrenal gland is developed by separating Gerota's fascia from the mesentery of the descending colon. Careful dissection of the left renal vein will allow identification of the adrenal vein coursing into its superior aspect opposite the gonadal vein. Working backward, the adrenal vein leaves the left renal vein, joins with the inferior phrenic vein and courses anterior to the adrenal gland to enter its hilum. Ligation of the left adrenal vein followed

by medial traction will allow dissection between the left kidney and the adrenal gland.

The right adrenal gland when approach transperitoneally begins with the medial mobilization of the ascending colon followed by Kocherization of the duodenum to expose the inferior vena cava. The right adrenal vein is a short vein that can be found superior to the right renal vein entering the vena cava posterolaterally. Sometimes an accessory vein can be found as it enters the inferior phrenic vein. Surgical control of this vein is very important since injury to the vein can cause profuse blood loss. The arterial blood supply as described above forms a plexus that can be controlled with surgical clips or vascular sealing devices (Ligasure®, Harmonic Scalpel®).

7. NEPHRECTOMY–NEPHROURETERECTOMY

Robotic nephrectomy and nephroureterectomy mirrors the steps of non-robotic laparoscopic nephrectomy: isolation, ligation, and division of the renal vasculature and its ligation, ureteral division, and division of the ligamentus and adventitial attachments of the kidney and then the ureter. The 5 mm scissors and Debakey forceps for the robot are the routinely used tips on the robot arm and the bedside assistant uses the suction-irrigation aspirator to keep the operative field dry. The Maryland dissector or the Debakey forceps can be used for hilar dissection.

7.1. Surgical Dissection and Exposure of Kidney

7.1.1. RIGHT KIDNEY

When the right upper quadrant of the abdomen is visualized transperitoneally, one could clearly see the hepatic flexure of the colon underneath the overhanging edge of the liver and the outline of the right kidney behind and lateral to the colon. If the kidney is involuted and small as in a multicystic dysplastic kidney, the outline of the kidney may not be visualized and the entire kidney might lie underneath the overhanging edge of the liver. On the other hand, a renal mass or a hugely dilated renal pelvis might make the kidney very obvious to identify and in fact shift the colon medially or laterally to the mass. Hence, it is important to visualize the colon and its hepatic flexure in its entirety and then start mobilizing the colon on line of Toldt lateral to the colon to prevent transmesenteric dissection on to the Gerota's fascia. Transmesenteric pyeloplasty has certainly been widely practiced but in our opinion we would not recommend an extirpative renal procedure that needs access to the renal hilum in a transmesenteric fashion. If a transmesenteric approach was made accidentally, one has to be careful to protect the mesenteric vessels to the colon and the colon itself and after the procedure is completed, the defect in the mesentery is better closed to prevent future herniations.

The line of Toldt is first incised at the level and lateral to the hepatic flexure. A plane is developed between the Gerota's fascia posteriorly and the mesentery of the colon anteriorly and medial mobilization of the mesentery is performed. The correct plane of dissection between these two layers is identified by a number of methods. The difference in the color of the fat of mesentery and the Gerota's fascia, the line of the coursing capillaries that can be visualized on the mesentery and when the mesentery is held by a Maryland dissector is moved side to side, any tissue that moves on the surface of the Gerota's should be dissected as part of the mesentery. Dissection of this plane medially at the level of the lower pole exposes the gonadal vein coursing cranio-caudally on the surface of the psoas muscle. At the level of the mid and superior pole, medial mobilization of the colonic mesentery exposes the duodenum. The duodenum should be dissected free from the surface of the Gerota's fascia and sometimes these attachments are strong enough that blunt dissection may result in serosal tears or worse perforations of the duodenum. Hence a careful sharp dissection with the robotic scissors without using diathermy should be performed on the lateral surface of the duodenum with the other arm of the robot pushing the kidney laterally and providing some counter traction.

7.1.2. Hilar Exposure and Dissection

Medial mobilization of the duodenum, Kocher maneuver, exposes the IVC and the thin fascial covering on the IVC is first dissected free to clearly visualize the right renal vein and right gonadal vein joining the IVC. At the level of the lower pole of the kidney, a plane is created above the gonadal vein leaving the vein in the retroperitoneum towards the surface of the psoas fascia and in this plane the lower pole of the kidney is lifted up toward the anterior abdominal wall. The upward traction of the kidney can be performed by the bedside assistant or by utilizing the fourth arm, the latter being more appropriate in older kids. This step is essential to prevent inadvertent damage to the gonadal vessels or the ureter, defines the anatomy, and provides clear circumferential view of the hilar vessels. The ureter is identified in this package and taken up with the kidney. This plane is dissected cranially to approach the renal hilum. The preoperative work up should be able to assess the number of hilar vessels, particularly any accessory polar vessels one might encounter during this step. The surgeon should be always looking for any accessory vessels particularly lower pole vessels during this approach. With constant traction of the kidney with one arm of the robot or by the assistant, the plane between kidney and psoas fascia is dissected to expose the hilar pedicle in a circumferential manner. The renal artery and renal vein is identified clearly, skeletonized, and created into separate pockets amenable to division. The vessels can be ligated and cut using variety of techniques including suture ligation, endovascular ligature devices or Hem-o-lock clips (Weck Closure Systems Research, Triangle Park, NC), or a combination of

the above techniques. The Hem-o-lock clips can be applied using a robotic arm loaded with the robotic clip applicator.

During the supra-hilar dissection particularly in the right side, it is important to note that the adrenal gland is anchored to the surface of the IVC by very short adrenal veins. Any upward traction to the kidney that is not adequately mobilized from the adrenal gland is only going to exert traction on the adrenal gland and tear these veins. Hence the suprahilar dissection should start with dissection of kidney from the adrenal gland without traction. This can be performed with a combination of blunt and sharp dissection close to the surface of the kidney parenchyma using the Maryland dissector with generous use of cautery. Once the superior part of the kidney is freed off the adrenal gland, the rest of the lateral attachments are taken down and the ureter is clipped last and the specimen is completely detached.

This part of the dissection can be sometimes made more difficult by the overhanging edge of the liver. Most times it is possible to move the adrenal and along with it the edge of the liver away from the line of vision and dissect with the left arm. If this is not possible, the assistant or the fourth arm may be utilized to lift the liver. If not using the fourth arm, a separate 3 mm port can be inserted either in the right upper quadrant or in the subxiphoid position to act as a liver retractor.

7.2. Left Kidney

The broad steps of nephrectomy are similar to the described for the right kidney. The variations in anatomy and other technical details are outlined below.

Lateral dense attachments of the spleen to the lateral abdominal wall are incised sharply to provide adequate mobilization of the spleen with the tail of the pancreas medially. With this medial mobilization of the mesentery, the hilar region of the kidney is exposed. The medial border of the kidney at this level is followed cranially to enter the plane between the pancreas and the kidney and caudally leads to the lower pole of the kidney. At the level of the inferior pole of the kidney, the kidney is lifted off the psoas fascia along with the ureter but leaving behind the gonadal vessels and this plane is developed cranially to approach the hilum. This step is essential to prevent inadvertent damage to the gonadal vessels or the ureter, defines the anatomy, and provides clear circumferential view of the hilar vessels. On careful dissection, the gonadal vein could be visualized to join the left renal vein. The renal artery and vein are then isolated and skeletonized, ligated and divided as described before. The plane between the adrenal gland and the kidney is then developed to spare the adrenals in patients where it is appropriate. The lateral fascial attachments of the kidney are divided and the ureter clipped and cut last to completely detach the kidney from its attachments.

7.3. Ureterectomy

Ureterectomy in children is usually performed when the ureter is grossly enlarged from either obstruction (ureterocele or ectopic insertion) or from high-grade reflux. In these cases, the indication for nephroureterectomy is poor non-function and/or recurrent infection.

The ureterectomy is performed after the kidney has been freed. It may be performed with the kidney attached or after it has been amputated. Either way, the ureter is separated from the surrounding area using a vascular sealing device. As the area of the iliac vessels is approached, the ureter is carefully separated from them as it runs anteriorly. The surgeon must decide whether a stump of distal ureter will remain at this point or whether it is important to trace the ureter into the bladder. If a stump is going to be left behind, it should be drained of its urine by inserting the suction-irrigator and the urine aspirated. If vesicoureteral reflux is present into this system then the stump should be closed off. If there is no vesicoureteral reflux, then the stump should be splayed open to allow further drainage and avoid a closed system that could lead to future surgical extirpation. If complete ureterectomy is performed, the distal ureter is traced to its entry into the bladder. Along this course, the vas deferens must be protected as the ureter courses under the vas deferens; in girls, the ureter runs under the uterine artery (water under the bridge).

7.4. Specimen Extraction and Drain Placement

Once the kidney has been freed from all of its investing tissue and its vascular supply, it needs to be removed from the body (Fig. 1). When the specimen is small and malignancy is not of concern, the kidney may simply be removed intact through one of the incisions, preferably a midline incision is extended for 2–3 cm.

However, if a malignancy is of concern or if the specimen is large and cannot be passed through the incision made for the port, it should be placed into a bag device passed intracorporally through a port. Depending on the size
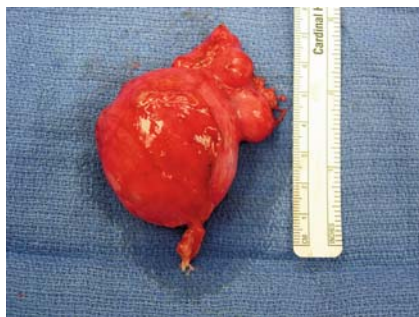
Fig. 1. Nephrectomy specimen of a multicystic dysplastic kidney.

of the kidney, one might use a Endocatch™ (Covidien, Hamilton Bermuda) bag or Lapsac® (Cook Medical, Bloomington, Indiana) as needed although in most children the Endocatch bag is adequate. If the nephrectomy is performed for benign pathology, it is possible to morcellate the specimen prior to removal and this can be performed intracorporally with the help of morcellator and manually morcellate it after placing the specimen in a morcellator bag.

Most nephrectomies do not need drainage of surgical site. Drains may be considered in special situations like removal of an infected pyonephrotic kidney or one half of a horse shoe kidney.

8. RESULTS

There is no published series of robotic nephrectomy in children to this date. Peters *(11)* has reported his experience with using robots for performing upper tract urological procedures in children, one among them was radical nephrectomy, felt that the robot had more maneuvering capability when compared to straight laparoscopy. He has performed robotic surgery in children as young as 5 years of age in spite of a noticeable restriction of working space. Robotic nephrectomy series has been reported in the adult literature *(15)* and was shown to be safe and feasible minimally invasive option for removal of kidney. A comparative series looking at laparoscopic nephrectomy and robotic radical nephrectomy reported comparable results between the two groups except the robotic group had longer operating times when compared to laparoscopoic group (221 vs 175 minutes, $p < 0.001$) *(16)*. Although the role of robot has been much more clearly established in reconstructive procedures, robotic radical nephrectomy has not been established to be superior to any existing options. It may serve as an effective learning curve procedure for the surgeon before performing more complex reconstructive upper tract procedures and at the same time, provides the patient with a minimal invasive option with outcomes comparable to the present-day gold standard for minimally invasive nephrectomy, i.e. laparoscopic nephrectomy.

9. COMPLICATIONS AND LIMITATIONS

Some complications of robotic radical nephrectomy are not unique to robotic assistance but are rather part and parcel of laparoscopic part of the procedure such as pneumoperitoneum, inadvertent thermal injury to bowel and other organs. Problems with the functionality of the robot in terms of console failure or arm failure are problems not unique to this procedure and are detailed elsewhere.

Complications specific to robotic nephrectomy are few and far between when the adult literature is analyzed. In a small series (15 patients each) *(16)* comparing laparoscopic nephrectomy and robotic nephrectomy in adults, the

robotic series had one conversion to open surgery and the operative time is longer in the robotic group as mentioned in the results section. But the length of stay, analgesic requirements, and transfusion rate were identical between the groups. Oncological outcomes were not different between the two groups. Another series reporting on 35 patients that underwent robotic nephrectomy reported no conversions to open surgery.

Primary limitations of the robotic system are the lack of haptic feedback and the cost of the instrumentation. Haptic feedback includes tactile sensibility (sense of texture of tissue that is being held in the robot arm) and force sensibility (realizing the force that is applied to the tissues and suture materials). Most recent literature *(17)* in this regard does provide some evidence for these innovative challenges are being met at an experimental level, although their clinical applicability still largely remains to be answered in the future.

Cost of robotic surgery has long remained an unanswered question due to lack of quality evidence in this regard. The cost of the da Vinci robot system (over a million dollars with the considerable ongoing expenses of servicing the equipment which is reported to be 10% of the cost in some papers *(12)* and the cost of semi-reusable instruments) is compared to open surgery with prolonged hospital stay, increased blood loss evidenced in the adult literature to justify the use of robot. But we could not find any study that compares the cost effectiveness of robotic nephrectomy when compared to laparoscopic nephrectomy either in the pediatric or in the adult literature.

10. CONCLUSIONS

Robotic-assisted nephrectomy, with or without ureterectomy as well as adrenalectomy are safe and feasible options when indicated in children. It has comparable outcomes with laparoscopic nephrectomy. It makes it possible for a surgeon who is a novice in straight laparoscopy to provide a minimally invasive nephrectomy option for his patient. The procedure also serves as an effective stepping stone in robotic surgery before performing complex robotic-assisted reconstructive procedures. The cost-benefit analysis and comparative outcomes of robotic radical nephrectomy are still to be established and remains largely undetermined.

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10 Robotic-Assisted Laparoscopic Heminephrectomy

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1. INTRODUCTION

Ehrlich et al. *(1)* first reported the use of laparoscopic nephrectomy in children, and Jordon and Winslow *(2)* reported the first laparoscopic partial nephrectomy (LPN) in a 14-year-old girl with bilateral duplicated systems. Since these reports, there has been a boom in the utilization of laparoscopy in pediatric urology, where it has been aggressively pursued as an alternative to traditional open surgery given its association with decreased postoperative pain, length of stay, and improved cosmesis. The recent advent of robotic-assisted laparoscopic surgery (RALS) allows for most heminephrectomy to be performed without needing to fully mobilize the kidney, a distinct contrast to open surgery. This helps minimize trauma and vascular compromise to the remnant pole *(3–5)*.

RALS has been shown to offer the same benefits of traditional free-hand laparoscopy, but with the added benefit of 3-dimensional, high-magnification optics, and fully articulating instrument arms. These added benefits, despite the initial financial investment have been credited with greatly reducing the learning curve associated with various surgeries, which is critical when the primary goal for most indications of heminephrectomy is to prevent infections, incontinence, and protect functioning renal and ureteral tissue. However, there is a lack of a consensus regarding the best surgical approach (i.e., transperitoneal, retroperitoneal (prone), or retroperitoneal (lateral) for a given indication. The utility of ureteral stenting and surgical bed drainage (i.e., Jackson-Pratt or Penrose) also remains undefined.

2. EMBRYOLOGY OF DUPLICATED URETERAL SYSTEM

In a duplicated ureter, an accessory ureteral bud develops from the mesonephric duct. If the two ureteral buds are widely separated on the mesonephric duct, the accessory bud develops proximally and inserts into the bladder with an ectopic orifice inferiorly. The crossing of the duplicated ureters and their insertion explain why the upper pole is frequently linked to an obstructed system, thus causing dysplasia during fetal development (Weigert-Meyer rule). Ureteral ectopia is at least twice as common in females as males *(6)*. While ectopia of one or both ureters is possible, ectopia of only the upper pole ureter is usually present because its late migration results in an abnormal insertion outside the bladder (i.e., urethra or vagina) *(7)*.

3. INDICATIONS FOR HEMINEPHRECTOMY

By far, the most common indication for heminephrectomy in children is a non-functioning dysplastic pole secondary to obstructive uropathy, ureterocele, reflux, and/or ectopic/duplex ureter *(8)*. Multicystic dysplastic kidneys (MCDK) that have not involuted may be candidates for robotic-assisted laparoscopic heminephrectomy (RALH). Indications for RALH for MCDK are increasing cyst size, cyst infection, or hypertension *(9)*. Lastly, segmental mesonephric blastemia would be a good candidate for RALH if it was possible to better to be discerned from nephroblastoma preoperatively.

While partial nephrectomy and heminephrectomy are most commonly performed in adults for malignancies, the most common malignancy in children, nephroblastoma is rarely a candidate for a minimally invasive surgical intervention owing to its large, bulky size, frequent invasion of perirenal tissue, and risk of rupture with subsequent seeding during dissection. In children, peripheral, well-circumscribed lesions with enhancement on contrast imaging may be considered for a laparoscopic intervention. The maximal size that is considered safe to be managed laparoscopically is approximately 4 cm in adults, but is yet to be defined in the pediatric population.

4. PREOPERATIVE EVALUATION

Patients may present with incontinence, flank pain, hematuria, recurrent urinary tract infection, vaginal discharge, change in bowel habits, or abdominal masses. A thorough preoperative evaluation includes a voiding cystourethrogram (VCUG), renal ultrasound, and MAG-3 diuretic renogram *(10)*. Occasionally, cystoscopy with retrograde pyeloureterogram, abdominal CT with intravenous contrast or intravenous pyelogram (IVP) are useful in further defining the anatomy and assessing for common urological findings associated with ectopia (i.e., ureterocele, ureteropelvic junction obstruction, renal ectopia, renal dysplasia, and reflux) *(6,7)*. In cases

where a neoplasm is suspected, a metastatic work up consisting of a chest and abdominal CT scan with intravenous contrast should be performed. A bone scan is primarily only useful in cases of nephroblastemia. Given the possibility for hemorrhage if the renal vessels are injured a blood type and cross is performed. Figure 1 demonstrates the results of typical preoperative imaging.
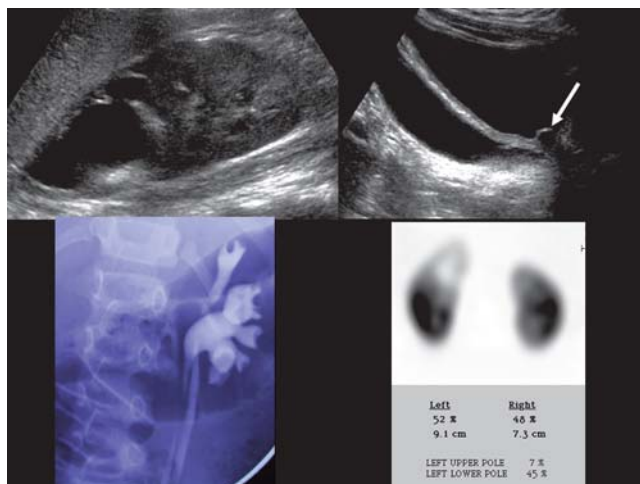
Fig. 1. Preoperative ultrasound, voiding cystourethrogram and nuclear medicine renogram demonstrating hydroureteronephrosis in a duplicated system with an ectopic ureter and mid-line ureterocele (*arrow*).

5. CONTRAINDICATIONS TO RALH

There are no specific contraindications for performing a RALH. Standard laparoscopic contraindications should be observed (i.e., hemodynamic instability, uncontrolled bleeding diathesis) *(11)*.

6. OPERATIVE CONSIDERATIONS

The night prior to surgery a mechanical bowel prep of polyethylene glycol and an enema is undertaken on either the inpatient or outpatient setting. Apply sequential compression devices to each calf for patients greater than 10 years of age. Subcutaneous anticoagulation is rarely indicated in patients without coagulopathy given the very brief period of postoperative bed rest.

Preoperatively, prophylactic a broad spectrum 3rd generation cephalosporin such as ceftriaxone is administered to cover skin flora and any specific urine organisms. Alternatively, clindamycin is also effective in those with penicillin or celphalosporin allergies. Robotic instruments and sutures typically needed are listed on Table 1.

Table 1
Typical Surgeon's Preference Card

Item	Quantity
Large gel rolls	2
Pillows	3
Instruments	
Minor pack	1
Prep pack	1
Foley 12 Fr	1
5 mm trocar	1
8 mm trocar	2
12 mm trocar	1
8 mm robotic microforcep	2
8 mm robotic Debakey forcep	1
8 mm robotic monopolar scissor	1
10 mm 30-degree robotic laparoscope	1
5 mm laparoscopic harmonic scalpel	1
10 mm laparoscopic specimen bag	1
Laparoscopic ultrasound (if neoplasm suspected)	1
Double-J stent (surgeon's preference)	1
Sutures	
2-0 Vicryl on UR-6 needle	3
5-0 Monocryl	2
Have available	
5 mm laparoscopic fan retractor	1
5 mm laparoscopic clip applier	1
Laparotomy kit	1
Dennis Brown retractor	1

Avoid nitrous-based inhalational anesthesia as this can cause bowel edema which can impact the size of the effective working field *(11)*. Children are more sensitive to the effects of carbon dioxide and the pressure of pneumoperitoneum or retropneumoperitoneum *(12)*, therefore recommended insufflation pressure is 10–12 mmHg *(13)*, lower than that is customarily used in adults. A transient modest decrease in intraoperative urine output is expected as a result of the pneumoperitoneum *(14)*. It is important not to increase the rate of intravenous fluid administration to overcome this as the minimization of insensible fluid losses in laparoscopy may result in fluid overload, especially in patients with cardiac comorbidities.

If the anatomy is uncertain, cystoscopy with retrograde ureterogram immediately prior to heminephrectomy can be both diagnostic and thera-

Fig. 2. Cystoscopy with stent placement into the normal ureter of a duplicated system with ectopia.

peutic (i.e., unroofing of an ureterocele). Some surgeons prefer to insert a Double-J ureteral stent into the normal ureter (Fig. 2) during cystoscopy to assist in identifying and protecting its vasculature during the laparoscopic excision of the duplicated ureter. Alternatively, a ureteral catheter can be placed in the normal ureter to inject methylene blue into the collecting system to identify inadvertent injury or confirm adequacy closure of an entered collecting system.

Occlusion of the main renal vessels is commonly performed during heminephrectomy in the adult population, since a relatively bloodless field greatly facilitates the proper identification and excision of a highly vascularized neoplasm, a far more common indication for surgery in this patient population. However, the most frequent indication of heminephrectomy in children involves operating on a poorly vascularized, non-functioning moiety; thus, clamping of the hilum is infrequently necessary.

When required, it is currently recommended that the renal vessels not be clamped for more than 30 minutes (warm ischemia) to maximize the recovery of renal function. Cooling the kidney to less than 20–25°C (cold ischemia) has been utilized to reduce cellular metabolism, allowing the surgeon 60–180 minutes of ischemic time while minimizing the risk of permanent tissue damage. In traditional open surgery, surgeons are readily able to cool the kidney by placing it on a bed of sterile saline slush. However, transferring this concept for cold ischemia to laparoscopic surgery has proven difficult.

Despite multiple published series on the methods to induce renal hypothermia, no system has proven to be either universally feasible or superior for use in laparoscopic partial nephrectomy. One proposed system is to use a laparoscopic specimen bag to completely cover the kidney and to deliver ice slurry via a laparoscopic port into the bag *(15)*. Unfortunately,

the ice slush delivery mechanisms require extensive amounts of custom-built equipment or trocars larger than those traditionally used in pediatrics *(16–18)*. Another proposed method of cold ischemia is to directly administer cold saline into the renal artery *(19,20)*. However, this method is limited by the risk for whole body hypothermia, the need for interventional radiology's assistance in placing an intraarterial line, and the theoretical risk of damage to the renal artery (i.e., hematoma and thrombosis). More promising techniques of inducing renal hypothermia (<20°C) include (1) irrigating the kidney with cold saline using a standard laparoscopic irrigator/aspirator *(21)*; (2) infusing cold saline transureterally in a retrograde fashion *(22–24)*; and the use of medications such as inosine *(25)*, captopril *(26)*, and tetrodotoxin *(27)* to enhance renal protection from ischemia. Of note, none of these modalities has been used in the pediatric population.

Since the hypoplastic, parenchyma of the affected pole is poorly vascularized, simple electrocautery is often sufficient for obtaining hemostasis in most RALH cases. However, many surgeons prefer to use commercially available hemostatic devices such as an argon beam coagulator, ultrasound coagulator, fibrin glue, cellulose, or suture bolsters. It is the preference of the authors to use an ultrasound coagulator to facilitate a near bloodless dissection and excision of the affected renal moiety. It is critical to reduce the insufflation to less than 3 mmHg at the end of the surgery to evaluate for any low-pressure venous bleeding, which may have been masked by the pressure of insufflation.

7. PATIENT POSITIONING AND SURGICAL CART DOCKING

Trocar placement and robotic cart docking are two of the most important steps to enable the surgery to progress safely and efficiently. Ergonomic arrangements will make assistant port(s) readily assessable with minimal conflict with robotic instrument arms. Fine adjustments to positioning are usually more efficiently achieved by moving the bed rather than attempting to reposition the surgical cart. Extensive padding of all points of contact (i.e., knees and arms) is required to avoid nerve palsies and pressure ulcers, especially in young children who have little fat for protection. The patient must be secured to the table to prevent movement or injury when rotating the bed intraoperatively. Specific patient positioning and surgical cart docking is dependent on the operative approach: transperitoneal vs. retroperitoneal. Advantages and limitations of transperitoneal vs. retroperitoneal approach are listed on Table 2.

8. STEPS OF THE SURGERY

8.1. Transperitoneal Approach

1. The patient is placed on the operating table with the affected side up (Figs. 3 and 4), and all points of contact (i.e., knees and arms) are padded. Position

Table 2
Benefits and Limitations to Surgical Approaches

Approach	Pros	Cons
Transperitoneal	• Familiar anatomy • More working space, especially in young children • Can perform concurrent extravesical ureteral reimplantation or ureterocelectomy • Shortest distance to the kidney • Avoid pedicle	• Theoretical risk of postoperative intraperitoneal adhesions (48,49) • Often limited working space and unfamiliar layout of anatomy. • Risk of peritoneal tear and subsequent conversion to open surgery
Retroperitoneal (Lateral)	• Less risk of subjecting peritoneum to complications (i.e., urine leak, infection and seeding) • Less interference from surrounding organs (i.e., liver, spleen, bowel) • Greater working space and more access to distal ureter than prone retroperitoneal approach, but requires lateral retraction to expose hilum • Theoretical reduction in postoperative intraperitoneal adhesions and easy conversion to lumbodorsal approach	• The use of a balloon dilator to develop the retroperitoneal space carries a risk of balloon rupture which necessitates meticulous retrieval of fragments which is especially critical if a peritoneal tear is present

(Continued)

Table 2
(Continued)

Approach	Pros	Cons
Retroperitoneal (Prone)	• Shortest distance to the kidney • Avoid pedicle • Less risk of subjecting peritoneum to complications (i.e., urine leak, infection and seeding) • Less interference from surrounding organs (i.e., liver, spleen, bowel) • Kidney falls anteriorly with gravity, exposing the hilar vessels without retraction • Ureter and pelvis posterior for easier dissection. • Theoretical reduction in postoperative intraperitoneal adhesions and easy conversion to lumbodorsal approach	• Often limited working space and unfamiliar layout of anatomy • Inability to perform total ureterectomy without adjunct inguinal incision (50) • Risk of peritoneal tear and subsequent conversion to open surgery. The use of a balloon dilator to develop the retroperitoneal space carries a risk of balloon rupture which necessitates meticulous retrieval of fragments which is especially critical if a peritoneal tear is present
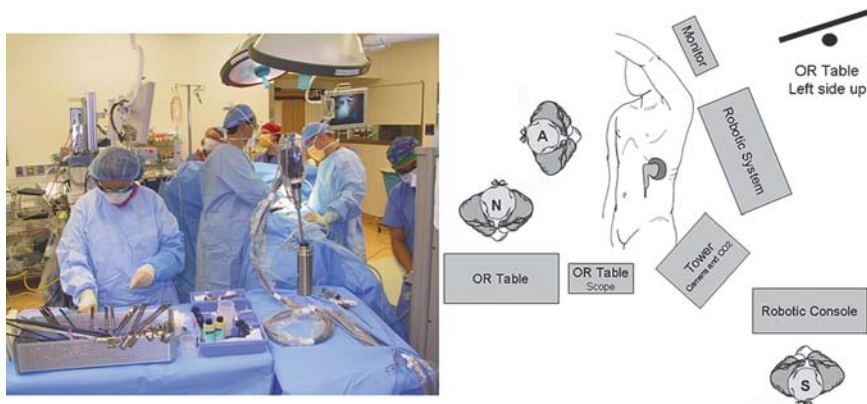
Fig. 3. Operating room set up.

Fig. 4. Patient positioning for a left transperitoneal heminephrectomy. Note the abundant padding for pressure points.

the patient on the edge of the table to provide amble room for the articulation of the camera arm over the side of the bed. This maneuver is essential in allowing for a full view of the abdomen. A combination of a roll under the nape of the back and rotation ("airplane") of the bed will put the patient approximately 45-degree angle off the table. Not enough angulation will prevent the bowel from sufficiently falling away from the kidney and hilum. Whereas too much rotation will cause the kidney to fall down

upon the hilum, both obstructing the hilum and creating a difficult angle of
approach for instruments.

2. Trocars are placed under direct visualization as indicated in Fig. 5. In
most patients an angle of 120–150 degrees between the trocars facilitates
a balance between being able to perform a distal ureterectomy, while still
retaining the ability to excise the upper pole moiety.

3. To dock the surgical cart, the surgical cart arms and instruments are posi-
tioned so as to mimic a patient in lithotomy position (Fig. 6). This helps
minimize interference between arms. Place Debakey forceps in the left
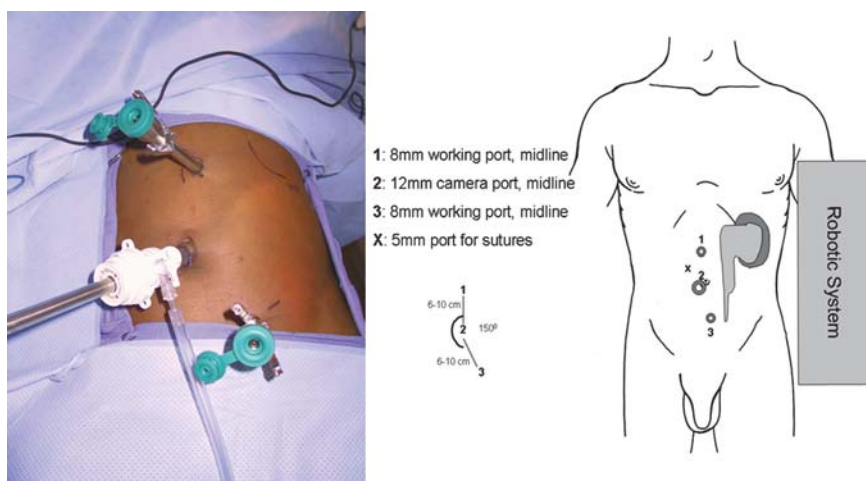
Fig. 5. Port placement for a left heminephrectomy.

Fig. 6. Docking of the robotic cart. Note the space between the surgical arms.

arm/hand (yellow) and monopolar scissors in the right arm/hand (green). Notice, the amble room available for camera movement as a result of positioning the patient close to the edge of the table.

4. Mobilize colon along white line of Toldt (Fig. 7).
5. Identify the kidney which is facilitated by the usually hydronephrotic affected pole (Fig. 8).
6. As a means to reduce postoperative pain and the need for postoperative narcotics, it is the authors' preference to aerosolize bupivacaine intraperitoneally prior to incising the perirenal fascia (Fig. 9) *(28)*.
7. Open the perirenal fascia to expose the kidney, ureters, and hilum (Fig. 10).

Fig. 7. Mobilization of the colon.
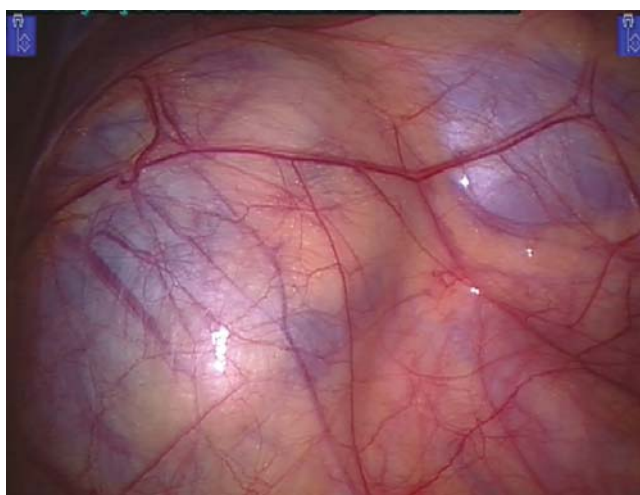
Fig. 8. Identification of the affected pole is facilitated by its dilatation.
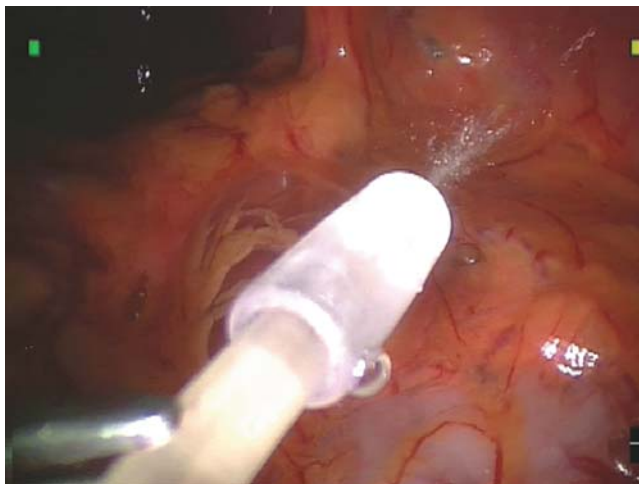
Fig. 9. Intraperitoneal aerosolization of bupivacaine.
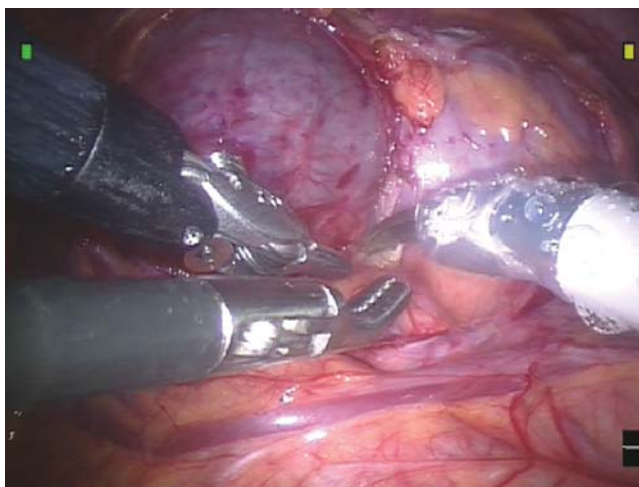
Fig. 10. Exposing the renal hilum.

8. Identify both ureters and trace the larger one to the upper pole (Fig. 11). Delay decompressing hydronephrotic pole until as late as possible to facilitate identification and dissection.

9. Mobilize the affected ureter distally while protecting normal ureter and its vasculature (Fig. 12). If possible, remove as much ureter as possible to prevent infection in the stump, which may require a subsequent surgery. However, it is reasonable to leave a small ureteral stump if no reflux is detected on the preoperative VCUG. In cases with an ureterocele/ectopic ureter the stump is left open.
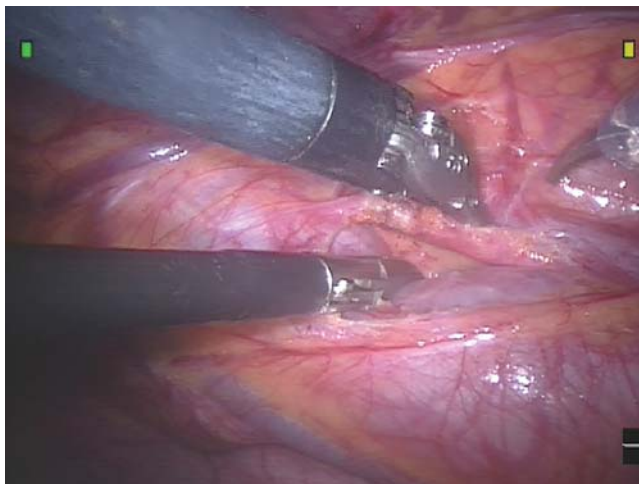
Fig. 11. Identification of the ureters.

Fig. 12. Isolation of the ureter from the vasculature.

10. Use ureter to manipulate kidney for mobilization (Fig. 13). Be careful when reflecting upward as you may avulse small feeding branches to the kidney.
11. Identify and dissect the vasculature to the affected pole (Fig. 14). If the anatomy of the vasculature is not obvious, temporarily occluding the vessel will cause parenchymal blanching in the dependent tissue. It is rarely necessary to occlude the main vessels, but if needed administer mannitol intravenously 10 minutes prior to clamping. Renal ischemia and methods of achieving cold ischemia are previously discussed. Dissection of the lower pole is similar to that of the upper pole, but the vascular supply must be
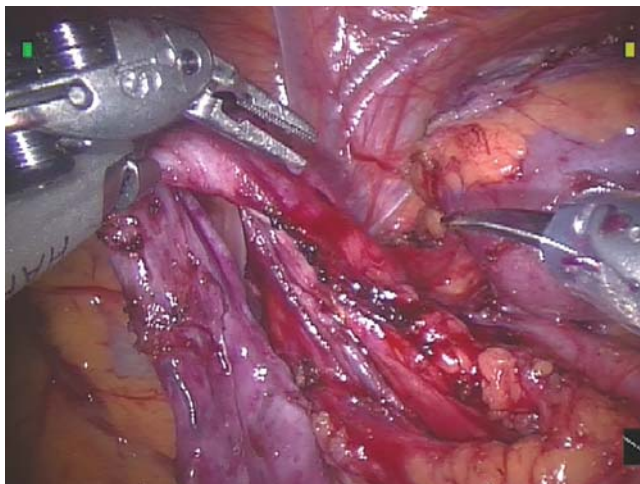
Fig. 13. Mobilization and dissection of the affected ureter.

Fig. 14. Identification of the vasculature.

definitively identified and protected as the upper pole vasculature usually branches from the main vessel to the upper pole.

12. Excise the affected pole along the concave plane (Fig. 15). Avoid entering the normal pole collecting system. If entered, close with 4-0 absorbable suture. Note the deep grove between the dysplastic and normal pole and the difference in thickness and color of the parenchyma.

13. Close the capsule over the exposed parenchyma with running 4-0 absorbable suture (Fig. 16). Place a mattress 3-0 suture over either a fat or gel foam bolster.

14. Because the unaffected pole is not mobilized, a nephropexy to avoid torsion to the remaining segment is not required.

15. Unlike the retroperitoneal approach the absorptive property of the peritoneum removes the need for a surgical bed drain. A ureteral catheter is left in the normal ureter and a Foley catheter is left to gravity.
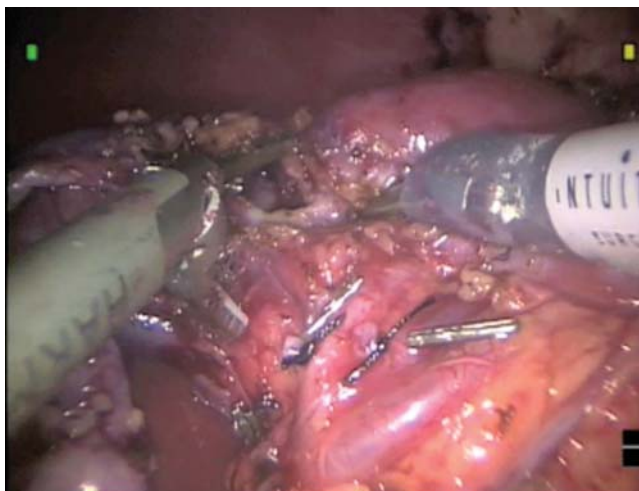
Fig. 15. Excising the affected pole.
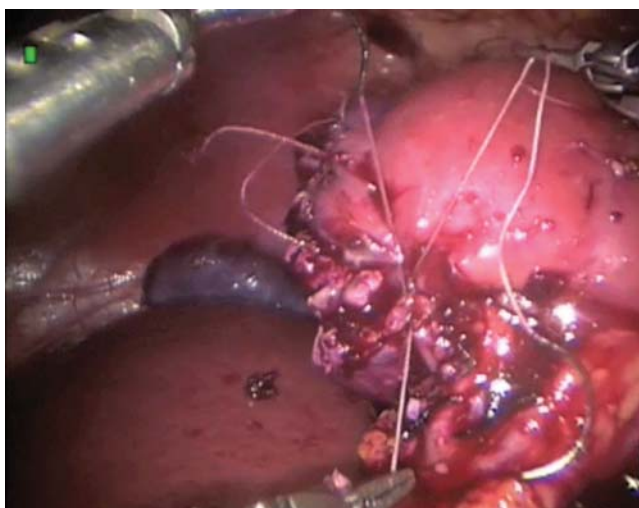
Fig. 16. Closure of the renal capsule.

8.2. Retroperitoneal-Lateral Approach

1. The patient is positioned on the operating table laterally with sufficient flexion to facilitate trocar placement between the last rib and iliac crest (Fig. 17). The authors prefer to use gel padding in young children and the kidney rest in young adults.
2. An open Hassen trocar is inserted 3 cm below the 12th rib. Gerota's is approached with a muscle splitting technique via blunt dissection along the lumbodorsal fascia. Anchoring this trocar with a purse string suture to

Fig. 17. Patient positioning for a retroperitoneal approach.

the fascia allows the trocar to be retracted, increasing the working space as needed. One must be careful to guide the dissection along the posterior wall to avoid violation of the peritoneum.

Fig. 18. Identification of the affected pole.

3. Identify the kidney which is facilitated by the usually hydronephrotic affected pole (Fig. 18).
4. A working space is developed with either gas insufflation, balloon dilator, or bluntly with a finger (Fig. 19) *(29)*. Maximizing and demarking the psoas muscle the working space prior to inserting the trocars is critical to assist in avoiding peritoneal tears, necessitating a conversion to a transperitoneal or open approach *(30,31)*.
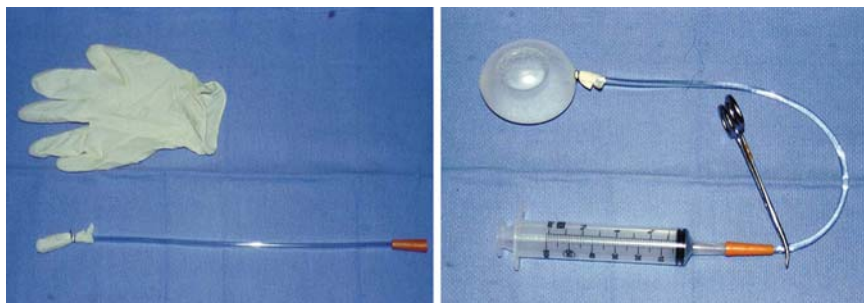
Fig. 19. Development of a retroperitoneal working space.
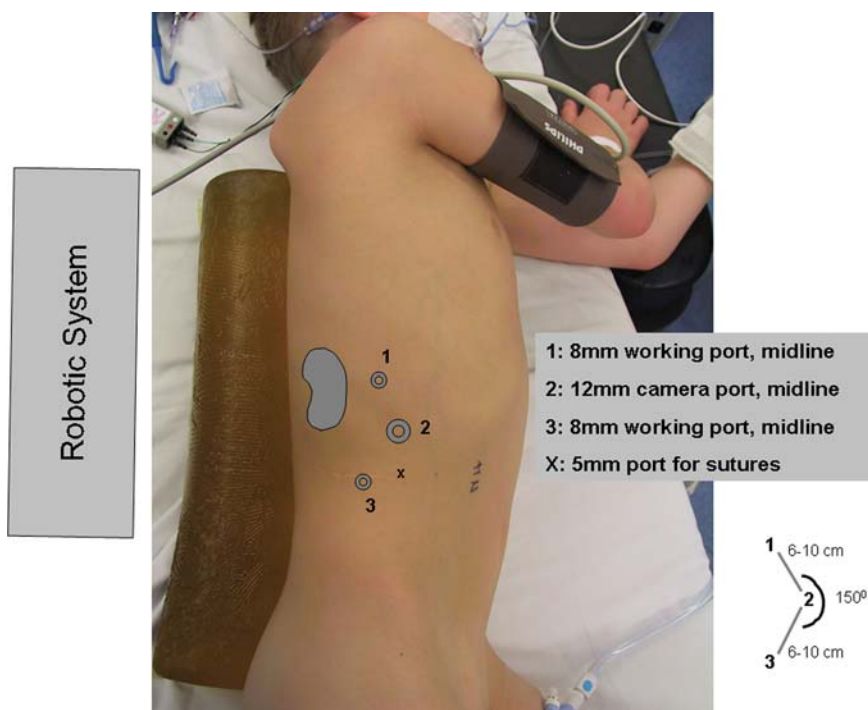
Fig. 20. Trocar placement for a left lateral retroperitoneal approach.

5. After the working space is developed a second trocar of 8 mm is inserted posteriorly in the costoverberal angle. The third trocar, the second 8 mm, is inserted along the anterior axillary line 10 mm superior to the iliac crest (Fig. 20).

6. The dilated, affected pole and ureter are identified and isolated along with the supplying vasculature (Fig. 21).
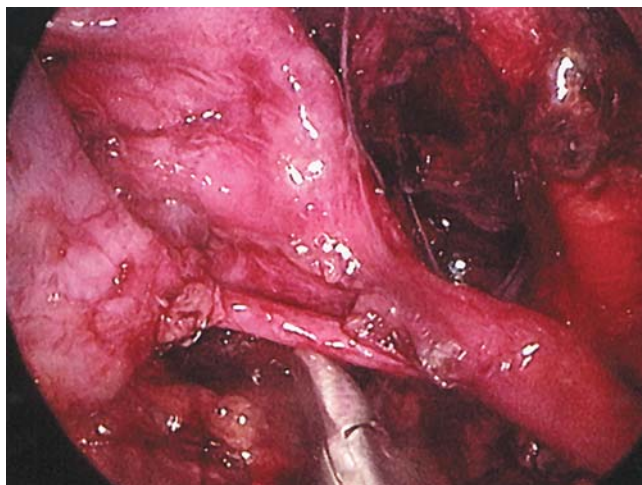
Fig. 21. Identification of the affected pole.
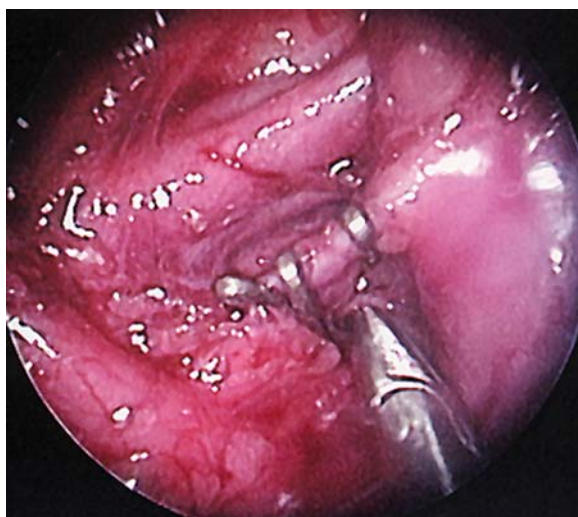
Fig. 22. Identification of the hilar vessels.

7. Identify renal pedicle and ligate the vessels supplying the affected pole (Fig. 22).
8. The distal ureter is transected and used to help manipulate the kidney (Fig. 23).
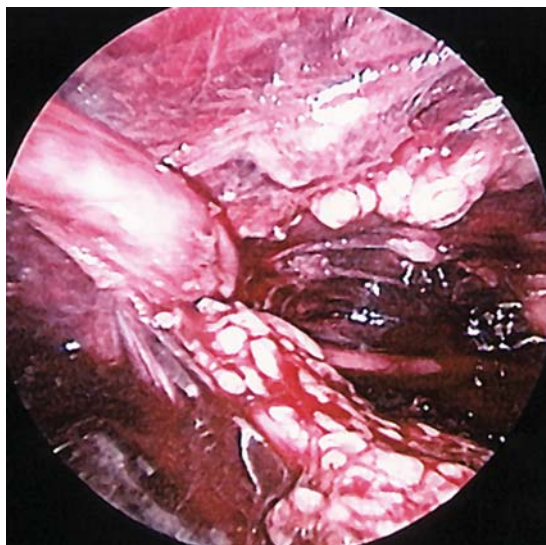
Fig. 23. Dissection of distal ureter.
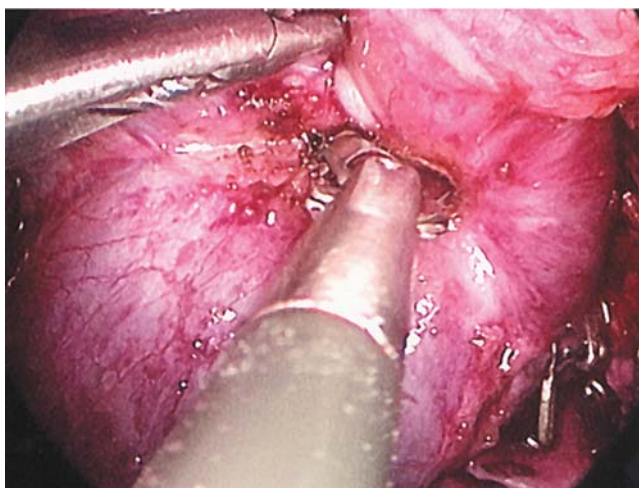
Fig. 24. Excision of the affected pole.

9. The affected pole is excised along a relatively avascular plain (Fig. 24). Great care must be taken to avoid entry into the collecting system of the normal pole.
10. The normal remaining kidney is checked for leaks and closed over bolsters (Fig. 25).
11. The authors recommend placing a penrose drain in the surgical bed due to the limited fluid absorptive ability of the retroperitoneum as compared to the transperitoneal approach. A Foley catheter is left to gravity drainage.
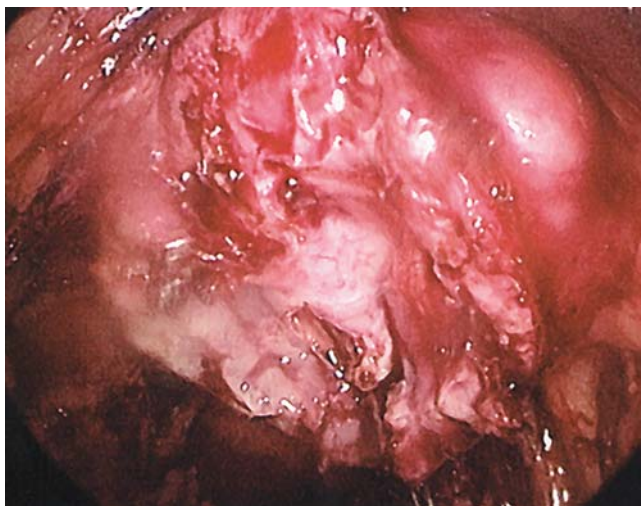
Fig. 25. Remaining normal pole prior to capsule closure.
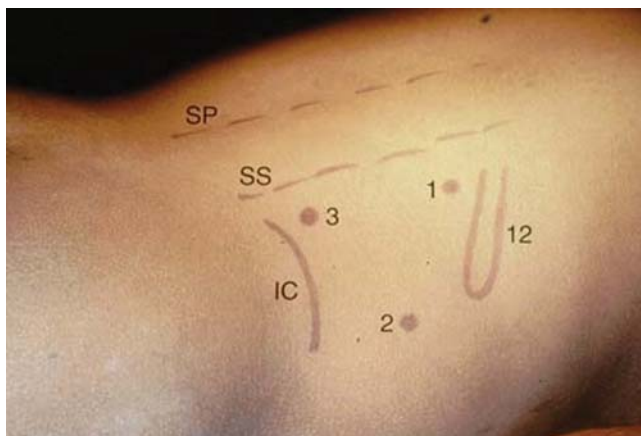
Fig. 26. Trocar placement for a left prone retroperitoneal heminephrectomy.

8.3. Retroperitoneal–Prone Approach

1. The patient is placed in the prone position with careful attention taken to pad all contact areas and protect the endotracheal tube.
2. The first trocar is inserted at the costovertebral angle at the edge of the paraspinous muscles (SS) and the 12th rib. The second trocar is placed laterally along the posterior clavicular line, also just above the iliac crest (IC). The third trocar is placed medially to the paraspinous muscles (SS), just above the iliac crest (Fig. 26).
3. The steps of dissection, development of a working space, identification and excision of the affected pole are the same as the lateral retroperitoneal approach.

9. COMPLICATIONS

There are few complications specific to performing a robotic-assisted laparoscopic heminephrectomy. One such complication is the failure of the robotic system (i.e., non-overridable fault) which necessitates either conversion to free hand laparoscopy or open surgery. Additionally, the undetected entry into the collecting system, damage to the normal parenchyma or ureter is possible. As with all intraperitoneal laparoscopic surgeries there is a risk, albeit low, of serious complications such as bowel perforation, trocar and Veress needle trauma to major blood vessels, spleen injury (left-side surgery), and liver laceration (right-side surgery). Pneumothorax secondary to diaphragmatic injury or transient bursts in pneumoperitoneum pressures using argon beam coagulation have been reported *(32)*. While rare, spleen injury (left-sided surgery) and liver laceration (right-sided surgery) are also possible.

10. POSTOPERATIVE MONITORING AND FOLLOW-UP

Immediate postoperative analgesia is achieved with ketorolac every 8 hours and morphine as needed. Codeine or equivalent per mouth is sufficient for most patients by postoperative day 1. A complete blood count (CBC) is obtained either intraoperatively or in the PACU. A follow-up CBC is obtained the morning after surgery. Typically, patients are started on a clear diet within 4 hours postoperative and advanced as tolerated to an appropriate "full" diet on the morning of postoperative day one. The Foley catheter is removed in the morning of postoperative day 1, unless otherwise indicated. Once patients are tolerating a diet, afebrile with no signs of wound infection, and able to void, they are deemed safe for discharge home. Of note, the authors do not require a return of bowel function as indicated by a bowel movement prior to discharge. Patients are discharged with antibiotics only if a vesicoureteral reflux is present or a catheter was left. Unless otherwise indicated, an ultrasound is performed at a month postoperatively

Table 3
Summary of Published Literature for Transperitoneal Approach

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospitalization	Complications	Follow Up	Author's Comments
Castellan et al. (34)	Retroperiteonal (16) v. Transperitoneal (32) Upper/lower-pole heminephrectomy	TP: Ureterocele (16), Ectopic ureter (13), VUR (3). RP: Ureterocele (6), Ectopic ureter (8), VUR (1), Caliceal diverticulum (1)	48	RP: 3 months–17 years (Mean 6.1 years); TP 45 days–17 years (Mean 2.8 years)	RP: 90–180 minutes (Mean 133); TP: 80–170 minutes (Mean 125)	TP: 0.5-5 days (Mean 2.6); RP: 1–6 days (Mean 2.3) * 5 patients undergoing concomitant surgeries	TP: 8 month old with pneumothorax secondary to diaphragm perforation requiring chest tube(1), 6 month old with postoperative HTN requiring medication likely due to small vessel injury(1), 11 month old requiring an excision of ureteral stump due to recurrent UTIs. RP: Peritoneal tear with conversion to transperitoneal approach (1), Conversion to open due to scarring and anterior pole vessels (1). 16 year old with urine leak(1), 12 month old with urinoma(1)	0.75–7.25 years (mean 3.5 years)	80% of complications in children <1 year. TP associated with increased difficulty identifying polar vessels, but RP avoids need for dissection of the main renal vessels. TP best approach when total ureterectomy required or patient <1 year.

(Continued)

Table 3 (Continued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospitalization	Complications	Follow Up	Author's Comments
Jordan Winslow (2)	Transperitoneal Upper-pole heminephroureterectomy (1)	Recurrent UTIs and incontinence with severe hydronephrosis and orthotopic ureterocele	1	14 years	Not Reported	POD #2	None.	6 months – "Both sides to be normal. No further incontinence or urinary tract infection"	
Janetschek et al. (4)	Transperitoneal Upper (9*)/Lower (5)-pole heminephrectomy. *(2) with concomitant ureterocelectomy and URI	Ectopic refluxing mega ureter (5), ectopic obstructed megaureter (2), reflux nephropathy (5), Obstructing ureterocele with non-functioning upper-pole (2)	14	5.4 years (0.6–14)	222 minutes (180–330) in group with no concomitant surgery	4.4 days (3–6) in group with no concomitant surgery	None	Not Reported	

(Continued)

Table 3 (Continued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospitalization	Complications	Follow Up	Author's Comments
Prabhakaran (45)	Transperitoneal Hem-inephroureterectomy	Duplex System with dysplastic upper pole moiety and VUR (1), Duplex kidney with dysplastic lower pole moiety and VUR (1)	2 of 6 (Combined series with nephroureterectomy)	3 months, 20 months (Mean 11.5 months)	20 months—225 minutes; 3 months—265 minutes	20 months—Not Specifically Reported, 3 months—7 days	Bleeding requiring transfusion(1)	Not Reported	Recommended the use of stay sutures "to elevate the abdominal wall, increase the anterior-posterior distance, and thus prevent intraperitoneal injury during trocar insertion."
Yao and Poppas (47)	Transperitoneal Upper (5)/Lower (1)-pole Hem-inephroureterectomy. Lower pole with concurrent open ipsilateral URI	Utereocele (2), ectopic ureter (1), reflux (1), non-fluctioning moiety with hydroureteronephrosis (2)	6 of 26 (Combined series with nephrectomy and nephroureterectomy)	1.6 years	200 minutes (90–315)	1 day (0.4-5*). *Concomitant open URI with ileus.	None	Not specifically reported	

(Continued)

Table 3 (Continued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospitalization	Complications	Follow Up	Author's Comments
Horowitz et al. (3)	Transperitoneal Upper-pole nephroureterectomy	12 ectopic ureters (1 bilateral, 2 with reflux), 2 ureteroceles	13	0.4–14 years (Mean 3.8 years)	70–135 minutes (Mean 100); 125 min for simultaneous bilateral LPN	2–4 days (Mean 2.4). Delays in hospitalization: fever (4), Not tolerating diet (1), Low HCT not requiring transfusion (1)	Decreased hematocrit (etiology not reported)(1)	"All reported overall satisfaction with medical and cosmetic results" via phone follow up	
Pedraza et al. (43)	Transperitoneal Bilateral Upper-pole Heminephro-ureterectomy (1)	Duplicated system with ectopic ureters (1)	1	4 years	440 minutes	2 day	None	Not Reported	
Mulholland et al. (42)	Transperitoneal Upper-pole heminephroureterectomy	Duplicated system with ectopia (1), Nonfunctioning upper pole with ureterocele (1)	2 of 17 (Combined series with nephroureterectomy)	3 months and 16 months	229, 165 (Mean 197)	<23 hours (Mean <23 hours)	Pneumothorax from diaphragmatic injury with intraoperative laparoscopic repair (1)	2 weeks	

(Continued)

Table 3 (Continued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospitalization	Complications	Follow Up	Author's Comments
Sydorak Shaul (46)	Transperitoneal Upper-pole nephroureterectomy	Duplex System with ureterocele (5), severe reflux (1), ectopic ureter (1)	7	5–15 months (Mean 10 months)	Mean 179 (including cystoscopy)	1-5 days (Mean 2.4 days)	"several years later"—Ureteral stump excision for treatment of recurrent stump infections. Incisional hernia (1) requiring repair. Conversion to transperitoneal due to lack of space (1)	4-51 months	"The retroperitoneal space may be too small a space to properly visualize the hilum and distal ureter in [infants]."
Piaggio et al. (44)	Transperitoneal Upper (11)/Lower (3) -pole hem-inephrectomy	Ectopic ureter (7), Ureterocele (3), VUR (3), UPJO (1)	14 of 34 (Combined series with LPN v. Open PN)	0.5 Years (0.34–13.3)	81–349 minutes (Mean 180); Last 7 LPN (Mean is 138)	2 days (1–6)	Omental hernia (1), Urinoma (1)	Not Reported	Not toradol since 2001 surgeon preference change. No benefit for RP v. TP. Preference for TP due to more working space and ability to completely excise ureter. Stressed the importance of learning curve upon operative time.

Table 3 (Continued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospitalization	Complications	Follow Up	Author's Comments
Breda et al. (41)	Transperitoneal Heminephroureterectomy	Upper-pole obstruction of duplicated system (3)	3	12, 13, 14 months (Mean 13 months)	120–160 (Mean 138 minutes)	1–4 days (Mean 2 days)	Postoperative UTI requiring IV antibiotics (1)	2 weeks	3 mm instruments may minimize approach-related trauma, improve cosmesis and recovery without increase in difficulty.
Chertin et al. (2007) (40)	Transperitoneal Upper-pole (5), Lower-pole (5) Heminephroureterectomy with concomitant STING (1)	Non-functioning moiety of a duplex kidney with ectopic ureter (4), ureterocele (1), VUR (5)	10 of 20 (Combined series with LPN v. Open PN)	3.6 years ± 1.3	Not Reported	2.7 ± 0.29 days	Conversion to open (1) due to injury to unaffected ureter	28 months (6–81 months)	Safe and recommended even for children <2 years of age
Miranda et al. (2007) (51)	Transperitoneal Upper-pole nephroureterectomy	Unilateral Duplex System(5) with ureterocele (1); Bilateral Duplex System with VUR (1) (Staged Surgery)	6	5–20 months (Mean 9.5)	120–160 min (Mean 135 min)	5–48 h; 2–24 h	None	Mean 18 months. DMSA showed stable or improved function in all infants.	Use retroperitoneal for >2 years for total nephrectomy

Table 4
Summary of Published Literature on Retroperitoneal Approach

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospital-ization	Complications	Follow Up	Author's Comments
El-Ghoneimi et al. (38)	Retroperitoneal upper-pole hem-inephroureterec-tomy (6) and ureteral reimplantation (2)	VUR (2)	8	1.2 years (mean 0.2 –3.7)	153 minutes (90–210)	3.4 days (2–5)	Conversion to open due to inability to identify polar vessels (3) also revealing duodenal tear (1/3), Renal vein injury requiring nephrectomy (1), peritoneal tear not requiring conversion to open (4)	Not Reported	
Borzi (36)	Randomized posterior RP (12) v. lateral RP (7) partial nephrectomy ± ureterectomy	Not Specifically Reported	19	pRP: 4.9 years (0.5–7); LRP: 5.2 years (0.5–12)	pRP: 75 minutes (55–135); LRP 85 (60–140)	Not reported	pRPA: UTI(2); LPRA: Renal vein tributary injury ->conversion to open (2), peritoneal tear which did not halt surgery (2)	pRPA with UTI likely secondary reflux into ureteral stump unable to fully excise with pRPA approach (2)	pRP less complete of a ureter excision in older kids as compared to LRP. Thus, >5 yoa preference for LRPA. pRPA "marginally safer", but treatment of choice for polar heminephrectomy due to excellent vascular control.

(Continued)

Table 4 (Continued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospital-ization	Complications	Follow Up	Author's Comments
El-Ghoneimi et al. (37)	Retroperitoneal upper (13)/lower (2)-pole hem-inephroureterec-tomy	Ureterocele (8), Ectopic ureter (4), VUR (2)	15	Median 5.1 years (0.4–17.6)	152 minutes (75–240)	1.4 days (1–3)	Conversion to open due to peritoneal tear(1). Urinoma managed con-servatively(1)	3 months - all patients with "no abnormali-ties in the remaining renal moiety"	"The lower pole is more technically demanding…identifying the polar vessels requires a full dissection of the pedicle and the line of demarcation is less evident that that for an upper pole…"
Lee et al. (39)	Retroperitoneal-prone (11)/Flank (3) upper (8)/lower (6)-pole heminephrectomy	Ectopic ureter (5), Ureterocele (2), VUR (6), UPJO (1)	14	1.9 years (0.2–6.6)	194 minutes (116–325) Excluding cystoscopy and concomitant surgery.	1.2 days if no con-comitant surgery	Urinoma managed conserva-tively(1)	26 months. Ipsilateral renal growth by sonography in all patients	"The lower pole nephrectomy was considered to be more technically demanding because of the more extensive dissection required." For patients less than 2 years of age (9) operative time, narcotic usage, LOS was similar and without complications.

(Continued)

Table 4 (Coninued)

Author	Procedure	Urologic Findings	Patients	Mean Age (range)	Mean Operative Time (range)	Length of Hospital- ization	Complications	Follow Up	Author's Comments
Wallis (35)	Retroperitoneal upper (18)/lower (5)-pole hem- inephrectomy	Ureterocele (10), Ectopic ureter (7), VUR (5), Bilateral VUR (1) with staged surgeries	22	4.6 years (0.3–18)	174 minutes (105–300). Last 13 procedures 156 minutes (105–216). Excluding cystoscopy.	2.2 days (1–5)	Conversion to open due to peritoneal tear and inability to develop adequate working space (3). Not considered complications by the authors and were excluded from analysis. Transient urine leak (3), seroma requiring aspiration (1), and fever (1)	33 months (range 3-56). Functional loss of residual moiety in two patients less than 1 year of age: POD #3 normotensive and clinically asymptomatic (1), 3 months postoperative requiring nephrectomy to alleviate HTN(1)	"...the retroperitoneal approach [is] preferable for heminephrectomy because it more closely resembles the approach used in open surgery...RPA may place the residual unit at high risk for ischemia in infants." "An argument could be made for TPA being more appropriate in small children because it affords a greater working space and potentially decreases the risk of damage to the residual moiety...decreases the amount of manipulation required." "We have elected to perform open heminephrectomy in children younger than 12 months."

to assess renal growth, proper drainage of the remnant pole, and degree hydroureteronephrosis. If VUR was demonstrated preoperatively, a VCUG is also performed at 3–6 months. If no reflux is observed antibiotics are discontinued.

11. REVIEW OF THE LITERATURE*

A summary of the current published literature on the transperitoneal and retroperitoneal laparoscopic heminephrectomy is provided on Table 3 and Table 4, respectively.

Trocars: Regardless of approach (TPA or RPA), the majority of case series recommended a 10 mm camera port and two –5 mm, instrument ports with an additional 5 mm port, as needed for liver retraction. These port placements were recommended in the context of free-hand laparoscopy, some the surgeons find these trocar sizes and quantity to be sufficient for RALH, but we find the motion of the 8 mm robotic instruments to be smoother than that of the 5 mm instruments, thus justifying the negligible increase in trocar size. The size of the robotic camera necessitates a 12 mm trocar, as compared to the 10 mm (or smaller) camera used in free-hand laparoscopy.

Hemostasis: There is a significant variation in the preferred method of maintaining hemostasis from electrocautery only to the combined use of argon bean and ultrasonic coagulation in conjunction with cellulose. We feel that the majority of the case, including the excision of the poorly vascularized affected pole can be performed with electrocautery alone, but the use of ultrasonic coagulation provides excellent hemostasis while excising the affected pole. While there is an additional cost associated with using this equipment, we feel that the improved visualization from the hemostasis achieved and the efficiency of the ultrasonic coagulation excision reduces operative times, thus minimizing the cost associated with its utilization. Additionally, the use of fibrin glue as part of the closing bolster helps prevent leaks which would potentially extend the length of hospitalization postoperatively.

Ureteral stenting: Only one series (El-Ghoneimi et al. *(38)*) utilizing a retroperitoneal approach specifically commented on the use of a ureteral stent. In that study, El-Ghoneimi et al. placed a ureteral stent to identify the normal ureter. Conversely, among the transperitoneal approach series most authors did place a ureteral stent to facilitate the identification and thus protection of the unaffected ureter. However, multiple series felt that the grossly dilated affected ureter found in most patients sufficiently enabled proper identification, negating the need for stenting once a higher level of surgeon comfort with the surgery and anatomy was obtained.

 *There is only one report of RALH in the English literature (Pedraza et al. *(43)*). All other data are from publications on free-hand laparoscopy.

Surgical bed drains: There was no consensus in the published literature. In our institution's experience the ability for the peritoneum to absorb fluid accumulation makes the placement of a surgical bed drain unnecessary in the transperitoneal approach. Conversely, due to the minimal absorptive abilities of the retroperitoneum, we routinely place either a penrose or bulb-suction drain during retroperitoneal approaches.

Postoperative narcotic utilization: Lee et al. *(39)* reported a mean postoperative morphine utilization of 0.4 mg/kg (0.1–2.5). Three patients required no postoperative narcotics and three had an epidural placed intraoperatively per surgeon preference in their series of 14 patients undergoing a laparoscopic retroperitoneal heminephrectomy. In the transperitoneal group, Chertin et al. *(40)* reported a mean narcotic requirement of 0.56 ± 0.29 mg/kg. Additionally, multiple authors advocated the use of ketorolac postoperatively. There were no reports of postoperative bleeding attributed to the use of ketorolac.

Return to eating/activity: In most transperitoneal series children were started on at least a clear diet within 6 hours postoperatively. No data were reported in the retroperitoneal literature.

12. COST ANALYSIS

There are no specific data specifically assessing the financial aspects of robotic-assisted laparoscopic surgery. However, Robinson et al. reported a mean charge of $6,123 for free-hand laparoscopic heminephrectomy as compared to $4,244 for that of the open surgery cohort *(5)*. Of note, the mean operative time in the laparoscopic group was significantly higher than that of the open (200.4 v. 113.5 min, $p < 0.005$). There was not a significant difference in the length of hospitalizations between the groups. While not specifically reported in the literature, the decreased operative times and learning curves associated with RALH as compared to free-hand laparoscopy will likely offset a portion of the cost associated with acquiring and utilizing the robotic system.

13. FUTURE DEVELOPMENTS/TOOLS/TECHNIQUE VARIATIONS

Intraoperative fluorescence imaging is an evolving, new technology which can help identify blood vessels, tissue perfusion, and urine flow in real-time (Fig. 27). This technology may be especially useful when assessing the often aberrant vasculature of the lower pole. Intraoperative imaging also has the potential to assist in protecting the normal pole and ureter, by early identification and minimization of tissue trauma.
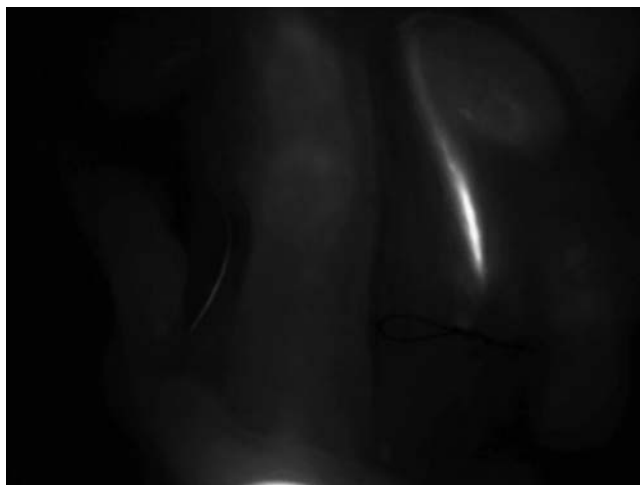
Fig. 27. Fluorescent imaging of a surgically induced left proximal ureteral obstruction in a mouse model. Note the normal peristaltic urine flow in the distal ureter of the right kidney.

14. CONCLUSIONS

Robotic-assisted laparoscopic heminephrectomy is superior to traditional open surgery in regard to cosmesis, postoperative length of hospitalization, and narcotic utilization. In comparison to free-hand laparoscopy, RALH offers the additional benefits of 3-dimensional, high-magnification optics, six degrees of instrument articulation, and a shorter learning curve.

While there are limited data directly assessing robotic-assisted laparoscopic heminephrectomy, the data for free-hand laparoscopy strongly supports a minimally invasive approach to heminephrectomy with or without ureterectomy. We feel that the added benefits of a robotic-assisted approach will further improve safety and the learning curve needed to achieve desired postoperative outcomes. RALH is safe even in the very young (2 months of age) *(33)*. While most authors recommend a transperitoneal approach in children less than 1–2 years of age due to the extra working space as compared to a retroperitoneal approach, there is no consensus on the age at which the working space afforded by a retroperitoneal approach is inferior to a transperitoneal approach *(34,35)*. The inability to reliably perform a distal ureterectomy in the prone RPA has limited its role in RALH as compared to a lateral RPA. As with many other surgical techniques for which there is not a definitive recommendation, the best approach is that which the surgeon feels most comfortable.

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11

Robotic-Assisted Laparoscopic Ureteral Reimplantation

Pasquale Casale

Abstract Laparoscopic antireflux surgery was described initially 10 years ago, but never achieved real popularity, presumably because of the difficulty in dissection and suturing. It has been reintroduced slowly in the last 4 years, but is still a technical challenge. Robotics facilitates intracorporeal suturing and has recently been deemed safe and feasible. Laparoscopic reimplantation with or without robotic-assisted surgical devices is currently being developed as an alternative to open surgery with great success. Robotics can be implemented in the different techniques of ureteral reimplantation including both extravesical and vesicoscopic approaches as well as in teaching modules.

Keywords Vesicoureteral reflux · Reimplantation · Intravesical · Extravesical · Laparoscopy · Robotics · Pediatrics

Urinary tract infection (UTI) occurs in 2–8% of children by 10 years of age *(1–4)*. Vesicoureteric reflux (VUR) is present in approximately 30% of children who have at least 1 urinary tract infection *(1–6)*. Accepted clinical data demonstrate that urinary tract infection in the presence of VUR can cause acute pyelonephritis and renal scarring *(4–8)*.

Treatment modalities for VUR vary and depend on the patient's clinical course. There is currently no consensus amongst health care professionals regarding when medical or surgical therapy should be used *(5–13)*. Most patients are placed on long-term antibiotic prophylaxis until either reflux spontaneously resolves, the patient achieves excellent potty habits in the face of lower grades of reflux, or surgical correction becomes indicated. Open ureteral reimplantation has been the gold-standard surgical intervention *(1–10)*. Subureteral injection of implant materials has also shown much promise in recent years with success rates approaching open surgery after two or more injections *(7)*.

Laparoscopic antireflux surgery was described initially 10 years ago, but never achieved real popularity, presumably because of the difficulty in dissection and suturing. It has been reintroduced slowly in the last 4 years, but is still a technical challenge *(13–31)*. Robotics facilitates intracorporeal suturing and has recently been deemed safe and feasible *(25–30)*. Laparoscopic reimplantation with or without robotic-assisted surgical devices is currently being developed as an alternative to open surgery with great success. Robotics can be implemented in the different techniques of ureteral reimplantation including both extravesicle and vesicoscopic approaches as well as in teaching modules. *(29–31)*

1. ROBOTIC EXTRAVESICAL URETERAL REIMPLANTATION

Successful laparoscopic extravesicle reimplantation has been described; however, the potential complication of newly developed voiding dysfunction, which can be up to 10%, remains a disadvantage of this approach *(8)*. Recently, robotic extravesicle reimplantation has shown that with the improved three-dimensional visualization, the nerves potentially can be spared alleviating the effects of voiding dysfunction seen with this type of approach. The preliminary results of robotic extravesicle reimplantation appear promising and reproducible.

The approach is to perform an extravesical, transperitoneal Lich-Gregoir procedure. Bilateral extravesical reimplantations have been associated with an increased risk for transient urinary retention although it has been claimed that laparoscopic procedures have less risk. *(8)* For unilateral procedures, an extravesical approach is used with the ports placed as shown in Fig. 1.

Fig. 1. Trocar placement for a left robotic reimplantation with ureteral tailoring.

Cystoscopy can be performed to place open-ended ureteral catheters to aid in the dissection. With the patient in the supine position an open technique is used to place the first trocar, the 12 mm camera port, in the umbilicus. The working ports, 8 or 5 mm, are positioned in the mid-clavicular line bilaterally, about 1 cm below the umbilical line. If the child has a pubo-umbilical length less than 8 cm, then the midline camera port must be placed above the umbilicus between the xyphoid and umbilicus to prevent robotic arm collision. The robotic is docked over the patient's feet.

The ureteral dissection is performed by incising the peritoneal reflection on the bladder sweeping the uterine ligament and pedicle posteriorly. The ureter is visualized just outside the bladder and mobilized beyond the uterine artery to the iliac vessels. Care is taken to avoid injury to the uterine artery. The posterior bladder wall is then cleared and the bladder partially filled. A detrusorraphy is made with the hot shears if using the 8 mm instruments and with the hook when utilizing 5 mm instrumentation. The author prefers the 8 mm hot shears as the hook tends to be extremely blunt for the detrusor dissection. The detrusorraphy is taken to the level of the mucosa for approximately 2.5–3 cm in a cephalad direction (Fig. 2). The detrusor is then dissected of the mucosa to facilitate wrapping of the ureter. One must ensure that the trough is deep enough as to avoid entrapping the ureter causing obstruction. Care must be taken to avoid any kinking or excessive compression of the ureter to prevent obstruction. Closure is performed proximal to distal or vice versa. In the latter, the ureter is well visualized but the needle needs to be passed under the ureter each time the suture is placed. I catch the adventitia of the ureter with each suture to ensure it does not slip back during the healing process. The mucosa should readily bulge from the trough as shown in Fig. 3. A Y-shaped mobilization around the hiatus of the ureter
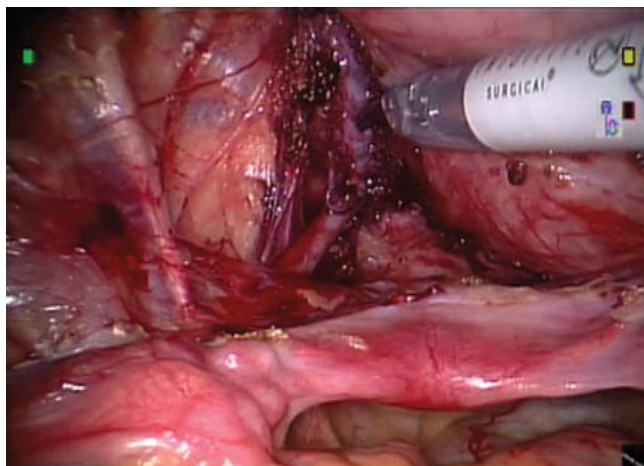
Fig. 2. Extravesicle reimplantation view of detrusorraphy.
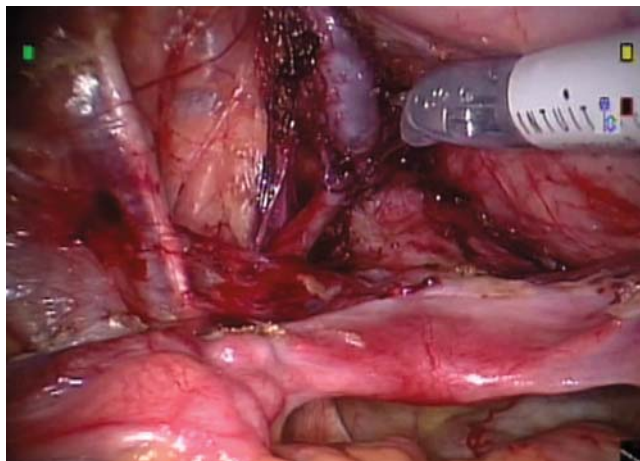
Fig. 3. Extravesicle reimplantation view of mucosa bulge after detrusor tunnel created.

is performed. There appears to be no reason to mobilize the hiatus circum-ferentially in the author's experience. The detrusor is then sutured over the ureter using 3-0 or 4-0 absorbable suture. A hitch stitch drawing the bladder upward might aid in exposure if the bladder is large upon filling. A catheter is left in the bladder overnight with a voiding trial in the morning.

2. TRANSVESICAL ROBOTIC URETERAL REIMPLANTATION

The laparoscopic Cohen procedure using a pneumovesicum was first described in a pig model in 2003 *(17)*. A description of its limitations has been illustrated and current work does not advocate the approach in blad-der less than 130 ml on voiding cystourethrogram studies *(27)*. There are few reports of this approach using conventional laparoscopy and only one using robotic assistance *(18,27)*. This technique is extremely challenging. The visualization and control are excellent and we must continue to develop this approach.

The patient is placed in the supine position with legs apart. The bladder is filled with saline solution through the urethra either via a flexible cystoscope or urethral catheter. Using an open technique or visualization via a flexible pediatric cystoscope, the 12 mm, 8 mm, or 5 mm camera port is placed in the midline at the bladder dome depending on the preferred size of the robotic telescope. A 3-0 absorbable suture secures the bladder wall and skin to the trocar. The working ports, either 8 or 5 mm, are positioned midway between the umbilicus and pubis at the mid-clavicular line intravesically and under direct visualization. Ports are fixed to the abdominal wall using a stitch which is also used to close the bladder. The bladder is filled with CO_2 to drain the saline and the robotic device is docked from the foot of the
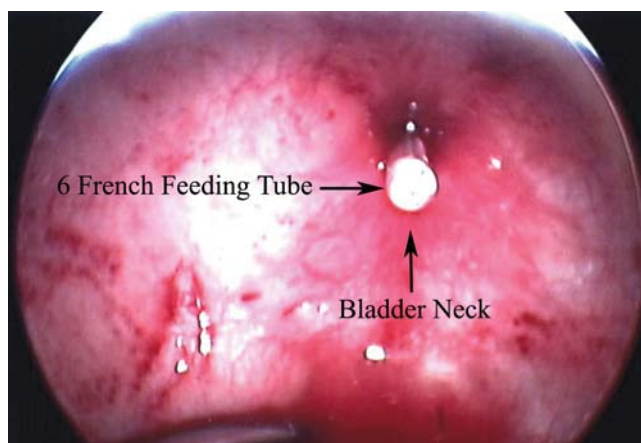
Fig. 4. Intravesicle view of bladder neck with a transurethral 6 French feeding tube used as a suction device.

bed over the patient's feet. A 6 French feeding tube is placed transurethrally and utilized as a suction device (Fig. 4). A pressure between 6 and 8 mmHg for CO_2 insufflation is employed because when higher pressures are utilized (greater than 10 mmHg) it appears that the bladders has spontaneous contractions in this author's experience. Although these contractions were uncommon, they completely disrupt visualization and can potentially dislodge the trocars since they are fixed in place on the robotic arm. Turning down the pressures seems to alleviate the problem; however, further investigation is warranted to see if this truly is an entity.

Similar to the open technique, ureteral dissection starts after placement of a 6 cm segment of a 5 Fr feeding tube or 4 Fr open-ended ureteral catheter, secured to the ureter with a 4-0 absorbable suture. Mobilization of the ureters is done as in the laparoscopic pneumovesical procedure using the hook or scissor cautery. The submucosal tunnels are created by dissecting with scissors from the original hiatus to the other side of the trigone, and incising the mucosa at the site of the new mucosal hiatus. Anatomosis of the ureters is performed after bringing them through the mucosal tunnel which can be performed in a Cohen Cross Trigonal or a Glenn-Anderson approach. The author favors a Glenn-Anderson approach when feasible. Anchoring sutures of 4-0 absorbable suture are used to secure the ureter to the bladder musculature and the mucosal cuff is attached with 5-0 absorbable suture. The hiatus is closed with 3-0 absorbable sutures with the mucosa over the original hiatus is closed with running 5-0 absorbable. The ureteral mucosa is matured to the bladder mucosa in an interrupted fashion with 5-0 absorbable sutures. The path of the ureter is checked after completion of the anastomosis using a feeding tube to ensure there is no obvious obstruction or twisting of the ureter.

The sutures should all be cut to 10 cm prior to placement in the bladder to facilitate manipulation. The sutures can be passed through one of the robotic working ports, or a 5 mm accessory port can be placed suprapubically if so desired. The author finds that the suprapubic trocar can be cumbersome in the smaller bladder. The working ports are removed and the bladder holding stitches are then tied to seal the bladder entry sight. The flexible cystoscope is used to inspect the inside of the bladder to confirm a water tight closure. The port sites are also closed at the fascial level. The bladder catheter is kept overnight with a voiding trial the next morning.

Postoperatively, an ultrasound is obtained in 1 month and a voiding cystography should be performed in 3 months until the surgeon's success can be correlated to their experience in the open approach. Accessing the bladder and closing the port sites remains a challenge. If a purely endoscopic technique is utilized, the author has found the use of a fascial closure device to be helpful. The device is employed under direct flexible cystoscopic visualization. The suture utilized is a 3-0 absorbable material.

A broader question is whether laparoscopic techniques using robotic assistance will be advantageous over open methods. Cosmetically, the scar for open reimplantation is low and nearly invisible after several years since one can hide it in the future suprapubic hairline. The post operative recovery is generally fast, and the success rate is high. Subjectively in this author's experience, the patients seem to have less bladder spasms with the majority of them lasting 24 hours after catheter removal.

The decrease in tissue manipulation with robotics might minimize trauma. The bladder is punctured instead of opened avoiding excessive force and reducing scarring of the bladder. Intravesical suturing and manipulation are very facilitated with robotics, therefore pursing further robotic development for bladder reconstruction is paramount. There have been more complex reconstructive procedures performed using the robotic device, including creation of a continent catheterizable stoma using the Mitrofanoff principle with appendix along with the creation of an antegrade continent enema channel. *(24,28)*.

3. SUMMARY

Robotic reimplantation is in its infancy. The procedure is technically demanding even for the experienced laparoscopic and robotic surgeons. The procedure has been deemed feasible and successful in the preliminary studies published thus far *(18,29,30)*. Even in the patients with a history of controlled, but severe dysfunctional voiding postoperative urinary retention or exacerbation of dysfunctional voiding has been rare *(29)*. There is a learning curve for the procedure. In the author's experience, the learning curve plateaus after 5–7 cases if the surgeon is facile with robotic interventions. The author is now at a point where post operative voiding cystourethrograms (VCUGs) are not performed. The technique has not deviated from the open

experience. The patients are followed clinically. If pyelonephritis were to develop, one would then obtain a VCUG, this being no different from the common practice seen with open reimplantation. The author recommends to video all robotic and laparoscopic procedures not only for a learning tool by residents and fellows, but it allows the surgeons to be critical of their technique and allow further improvement. It appears to be beneficial and recommend this practice especially in the early stages of developing a robotics or laparoscopic program.

Robotic surgery is already playing a part of pediatric urologic surgery. In the future, it will look different than it does now because of technologic and procedural innovations. The inherent value of precise visualization, tissue handling, and reconstruction, coupled with the reduced morbidity of laparoscopic surgery, suggests the potential value of these technologies and methods. Although there is much development to be done, the early results are encouraging. Pediatric urologists specifically, and pediatric surgical practitioners in general, must be involved in the evolution of these techniques and devices, to prevent having to adapt adult surgery–oriented systems to pediatric patients. Pediatric urologists need to be involved in this development actively to guide its course.

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12 Robotic-Assisted Laparoscopic Bladder Augmentation

Raj K. Goel and Jihad H. Kaouk

Abstract The application of minimally invasive surgery continues to expand in the urological community. However, more complex reconstructive laparoscopic procedures are often performed by experienced surgeons mainly due to difficulties with intra-corporeal suturing. Limitations with standard laparoscopy have now been overcome with the introduction of the robotic surgical platform. Robotic assistance allows surgeons to perform complex procedures with greater comfort, visibility, and flexibility. Robotic-assisted pediatric procedures now include ureteral reimplantation, pyeloplasty, orchiopexy, and nephrectomy. Recently, bladder augmentation with robotic assistance has been made possible for the pediatric patient.

Keywords Laparoscopy · Robotics · Pediatric · Bladder · Augmentation

1. INTRODUCTION

Minimally invasive surgery has an established foundation in adult urology for both extirpative and reconstructive procedures. Pediatric laparoscopic surgery as both a diagnostic and therapeutic modality is also gaining popularity. Reconstructive laparoscopic surgery however requires significant expertise and skill to perform intra-corporeal suturing. A variety of pediatric reconstructive procedures are available; however, surgeons are reluctant to employ the laparoscopic approach given the small working space and technical demands of intra-corporeal reconstruction *(1)*. Recently, reports of advanced laparoscopic and pediatric robotic procedures are emerging in specialized centers *(2)*.

In 2001, the Food and Drug Administration approved the application of a robotic surgical platform in adult urology (daVinci Surgical System, Intuitive Surgical, Inc, Sunnyvale, California). Since its introduction,

robotic-assisted surgery has gained acceptance within the adult and pediatric urologic community. The robotic platform facilitates intra-corporeal surgery with articulating instruments, tremor reduction, and 3-D magnification, which are all limited with standard laparoscopy. Through technical modifications to accommodate the pediatric patient, robotic reconstructive procedures such as pyeloplasty, partial nephrectomy, and orchidopexy (3) have been successfully performed. Ureteral implantation performed intra- and extra-vesically for reflux disease has also been made possible with robotic assistance (4,5). Recently, robotic-assisted bladder augmentation for the pediatric patient has been described (6,7).

2. INDICATIONS

Bladder augmentation is an invaluable surgical procedure used in the treatment of small, non-compliant bladders in both adult and pediatric patients. Although various conditions may require bladder augmentation, the pathophysiology in the pediatric population is often secondary to spinal cord dysraphisms. Despite non-surgical approaches, failed treatment of high intra-vesical storage pressures can result in upper tract deterioration and subsequent renal impairment (8,9). The aim of bladder augmentation is to re-establish a low-pressure urinary reservoir, to preserve renal function and to maintain urinary continence. Surgical methods available for bladder augmentation include autoaugmentation (10) and enterocystoplasty using various intestinal segments (11).

Autoaugmentation attempts to maintain the urothelial lining of the bladder while increasing both compliance and capacity. A diverticulum created by a detrusorectomy leads to the out-pouching of urothelium and lamina propria in an attempt to improve intra-vesical pressures. Surgically, autoaugmentation is less morbid and does not require complex reconstructive surgery. By avoiding the interposition of a bowel segment as in enterocystoplasty, metabolic complications, mucus production, and intestinal malabsorption are avoided (12). Although autoaugmentation is minimally invasive, it is not widely utilized as it has failed to achieved the same level of success compared to enterocystoplasty (13,14).

Enterocystoplasty attempts to correct the non-compliant bladder by incorporating a detubularized and reconfigured segment of bowel to the bladder. Various intestinal segments have been described in an attempt to reduce the metabolic sequalae encountered when the intestinal epithelium encounters urine. Each procedure is delineated by the respective bowel segment used: gastrocystoplasty, ileocystoplasty, cecocystoplasty, and ileocecocystoplasty. Technical differences among these segments are beyond the scope of this chapter, however, ileocystoplasty is the most common and the most familiar form of augmentation performed and will be discussed here.

Prior to considering surgical management, it is imperative to maximize non-surgical treatment of a non-compliant bladder. If persistent high

intra-vesical pressures are encountered despite anticholinergics and regular catheterization, bladder augmentation should be considered. Prior to surgery, upper tract imaging, cystography, and provocative urodynamics are essential to rule out underlying abnormalities of the kidneys, bladder and urinary sphincteric function.

3. CONTRAINDICATIONS

Contra-indications for enterocystoplasty include active urinary tract infections, pelvic malignancy, incomplete upper and lower urinary tract evaluation, previous bowel irradiation, inflammatory bowel disease, and anticoagulation. Relative contra-indications include multiple abdominal surgeries and poor patient and/or family compliance. Following reconstructive surgery, pediatric patients rely on the care provided by a parent/guardian and it is essential that care givers adhere to and understand post-operative instructions such as catheterization schedules. Failure to do so may result in complications such as frequent urinary tract infections, stone formation, and potential bladder augment rupture. Contraindications specifically to robotic-assisted surgery include general contraindications in addition to an inadequately trained surgical team to the robotic platform and age inappropriate robotic instrumentation.

4. PATIENT PREPARATION

After complete pre-operative evaluation, mechanical bowel preparation is performed one day prior to surgery. Often, patients with neurogenic bladders have chronic constipation which may lend itself to more aggressive bowel cleansing. If aggressive bowel preparation is required, caution must be exercised in the pediatric patient with limited reserve to avoid dehydration. Peri-operative antibiotics are usually provided to ensure coverage of both enteric and urinary pathogens. Cystoscopy performed under general anesthesia the day of surgery ensures no underlying intra-vesical pathology and allows placement of ureteral catheters to aid in identification of the ureteral orifices at the time of bladder augmentation.

5. TECHNIQUE

The patient under general anesthesia is placed in supine position with appropriate padding in 30º Trendellenburg. This position allows small bowel contents to migrate cranially maximizing exposure to the narrow pediatric pelvis. The entire abdominal wall and perineum is prepped for complete access to the abdomen and to the intra-operatively placed Foley catheter. Intra-abdominal access and insufflation can be achieved by an array of techniques including the Veress needle, open Hasson, or use of an optical trocar. All modalities have proven efficacy and choice of technique relies on

comfort and experience of the pediatric urologist. Intra-abdominal pressure in the pediatric patient should not exceed 8–10 mmHg to reduce the hemodynamic effects of pneumoperitoneum.

Pediatric patients pose a challenge for trocar placement due to the limited abdominal surface area and wall thickness. Exact trocar placement in children becomes essential as differences in millimeters may result in significant limitations in instrument range of motion. Modifications to the port placement used in adult robotic pelvic surgery in which ports are positioned in a "fan" configuration are typically used. During robotic instrument exchange, rapid dessuflation can result in trocar dislodgement. A method devised to prevent this include suturing the trocar to the abdominal wall so the trocar-abdomen unit move as one during dessuflation *(15)*. Availability of pediatric 5 mm trocars and respective instruments has allowed greater distance between adjacent trocars to prevent external instrument clashing. Finer instruments also improve manipulation of delicate tissues and suture material commonly used during pediatric procedures. Table 1 outlines the necessary instrumentation required to perform bladder augmentation in the pediatric patient.

Table 1
Pediatric Robotic-Assisted
Bladder Augmentation

Pediatric rigid cystoscope
Age specific ureteral catheters
Age specific Foley catheter

Suture material
3-0 Vicryl
Endoscopic stapling device

da Vinci Robotic Equipment
   5 mm Robotic trocars
   Bipolar electrocautery
   Monopolar endoshears
   Needle drivers
   Prograsp forceps

Jackson-Pratt Drain

Following intra-abdominal access and port placement, a segment of ileum is selected to perform bladder augmentation. Typically, a segment of ileum 15 cm proximal to the ileocecal junction, measuring 20–40 cm in length is identified. If the distal ileal segment is removed, malabsorption of essential vitamins and potential intractable diarrhea can result. It is important to ensure that the desired ileal segment along with its mesentery have sufficient length to reach the bladder without tension. Stay sutures are placed at the

proximal and distal ends of the chosen ileal segment in order to delineate the mesenteric vessels. Control of branching vessels by bipolar electrocautery is preferred to limit thermal energy spread to adjacent viscera. Following vascular division, the bowel segment is divided using endoscopic stapling devices at either end. The isolated segment is directed toward the pelvis and reconstitution of the remaining ends of bowel is performed (Fig. 1).
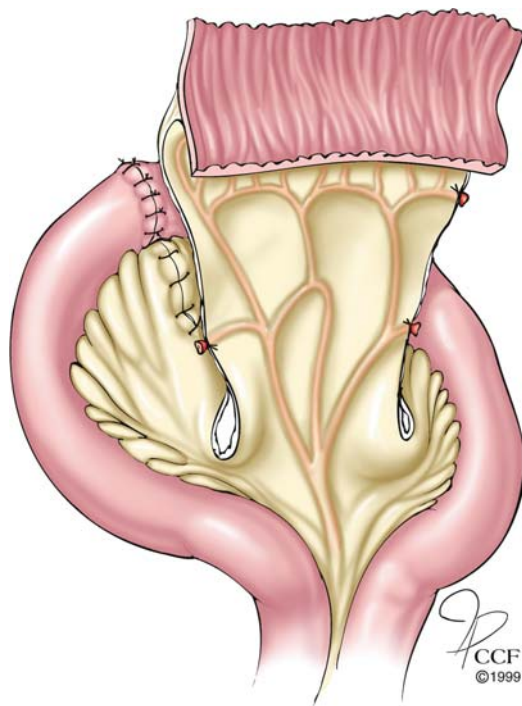
Fig. 1. An ileal segment is isolated along a broad based mesenteric pedicle and detubularized as shown. Entero-enterostomy is then performed to re-establish bowel continuity using sutures or stapling device. Mesenteric edges are re-approximated to avoid internal bowel herniation.

Methods to re-establish bowel continuity include both intra- and extracorporeal methods with a sutured or stapled technique. Superiority of either method has not been established; however, laparoscopically sutured intracorporeal ileo-ileostomy is technically demanding. To ease frustration and maintain familiarity, an intra *(6)* or an extra-corporeal stapled approach *(16)* for the bowel anastomosis has been described. Following re-anastomosis, the mesenteric window is closed with interrupted Vicryl sutures to prevent internal bowel herniation. Care must be taken to avoid constriction of the ileal segment's mesentery during this maneuver.

The isolated ileal segment is then detubularized along its anti-mesenteric border and reconstructed in a U-shaped configuration using absorbable suture (Fig. 2). This necessary step maximizes the overall bladder volume
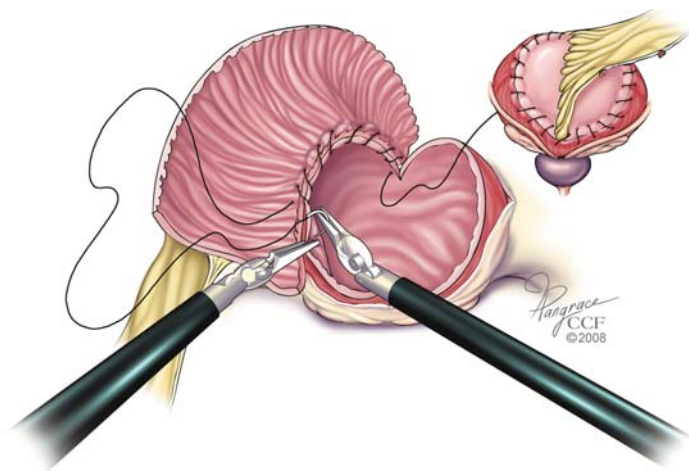
Fig. 2. Detubularized ileal patch is sutured to the bivalved bladder using a continuous suture as shown. Inset shows the completed ileal bladder augmentation.

achieved by the ileal segment. Enteric spill during both detubularization and reconstitution of bowel should be kept to a minimum to reduce intra-peritoneal inflammation and infection. A large proportion patients under-going bladder augmentation have ventriculo-peritoneal shunts due to their underlying spinal dysraphism. Although a theoretical concern, ventriculo-peritoneal shunts do not need to be externalized as shunt infections are rarely reported during clean-contaminated procedures *(17)*.

After preparation of the ileal patch, the bladder is released from the ante-rior abdominal wall and the space of Retzius is developed. Management of the native bladder to accommodate the ileal patch can include a supra-trigonal cystectomy or simply dividing the bladder in the anterior poste-rior dimensions. The latter less morbid approach is usually preferred. The ureteral catheters placed cystoscopically can be identified as posterior divi-sion of the bladder ensues. Hemostasis is gently performed with bipolar cautery to avoid excessive injury to the bladder mucosa.

The U-shaped ileal patch and its respective mesentery are now drawn into the pelvis adjacent to the bladder. The ileal segment is positioned so that the epithelial lining will become the intra-vesical component of the aug-ment. The posterior anastomosis is initiated first using absorbable suture (3-0 Vicryl) as exposure becomes limited following the anterior anasto-mosis. Non-absorbable sutures are avoided as they form a nidus for stone formation and infection. An interrupted or continuous suture configuration can be used so long as the integrity of the anastomosis is confirmed. The running anastomosis has an added benefit of providing hemostasis to both bladder and bowel edges which limit the use of electrocautery. To avoid the "purse string" effect which may compromise overall capacity, the suture is

intermittently locked. After completing the anastomosis, a Foley catheter is left in situ, as are surgical drains to monitor for a post-operative leak. Although still commonly used, supra-pubic catheters can be avoided as adequate surgical drainage and irrigation can be achieved with the urethral catheter.

6. RESULTS

In the early 1990s, autoaugmentation and enterocystoplasty were successfully performed in the pediatric patient by laparoscopic means *(18,19)*. Both procedures were performed intra-corporeally without open conversion and limited complication. Recently, additional reports of pure laparoscopic bladder augmentation have been described *(16,20,21)*. Unfortunately, the laparoscopic approach did not disseminate significantly amongst urologists given the technical demands of the procedure.

Since the development of robotic-assisted surgery, the applicability to the pediatric patient has been well established and considered safe *(22,23)*. Bladder augmentation has now been recently described in both the porcine model *(7)* and the pediatric patient (*6*). Although technically feasible, pediatric robotic-assisted bladder augmentation is challenging as suturing and handling bowel is limited by the small working space and lack of haptic feedback. Concerns have been already raised regarding potential central nervous system shunt infections, increased duration of the procedure and cost factors associated with the robotic platform. Although laparoscopic surgery has demonstrated benefits in adults, an advantage of a minimally invasive approach in pediatric patients has not been established. As familiarity and use of the robotic platform continues, the number of potential procedures performed in the pediatric population will grow exponentially. Currently, the robotic approach has already demonstrated efficacy in other pediatric procedures (*3*). As technical modifications to the surgical platform continue, the safety and efficiency of pediatric robotic surgery may potentially grow in parallel.

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13 Other Robotic-Assisted Laparoscopic Genitourinary Operations

Neel P. Shah and Jeffrey A. Stock

Abstract As with all applications of new technology we are compelled to ask: Does the use of this new technology lead to equivalent or better outcomes than existing procedures? This chapter will review the published case reports and series describing a diverse group of robotic-assisted pediatric urologic procedures, including bladder autoaugmentation and appendicovesicostomy (Mitrofanoff procedure). We will also present our experience in extending the use of this technology.

Keywords Bladder autoaugmentation · Appendicovesicostomy · Retrocaval ureter · Bladder diverticulum · Laparoscopy · Robotics · Pediatrics

As with all applications of new technology we are compelled to ask: Does the use of this new technology lead to equivalent or better outcomes than existing procedures? To paraphrase Willet Whitmore, "Is it possible to perform this procedure with the robot? Is the robot necessary for this procedure?" This chapter will review the published case reports and series describing a diverse group of robotic-assisted pediatric urologic procedures. We will also present our experience in extending the use of this technology. I believe, in well-selected patients that it is "possible" to perform many pediatric urologic reconstructive procedures with the robot. Over time and with increased experience using the da Vinci system it will become clearer in which procedures the robot "is necessary."

1. BLADDER DIVERTICULUM

Regardless of etiology, bladder diverticula arise as a mucosal herniation through a muscular defect in the bladder wall. The incidence of bladder diverticulum is 1.7%, with the majority of cases being seen in males *(1)* (Fig. 1). While there are no strict guidelines, indications for intervention may include recurrent urinary tract infections (UTI), vesicoureteral reflux (VUR), urinary retention, or voiding dysfunction *(2)*. Traditionally, surgery has been performed via an intravesical approach; however an extravesical or combined approach has been described *(1–3)*. While there is considerable laparoscopic experience in adults, this approach has not been readily applied to the pediatric population *(4)*. In a case report, Kok et al. in 2000 performed an extravesical laparoscopic excision of a congenital bladder diverticulum in one child *(5)*. More recently, robot-assisted bladder diverticulectomy has
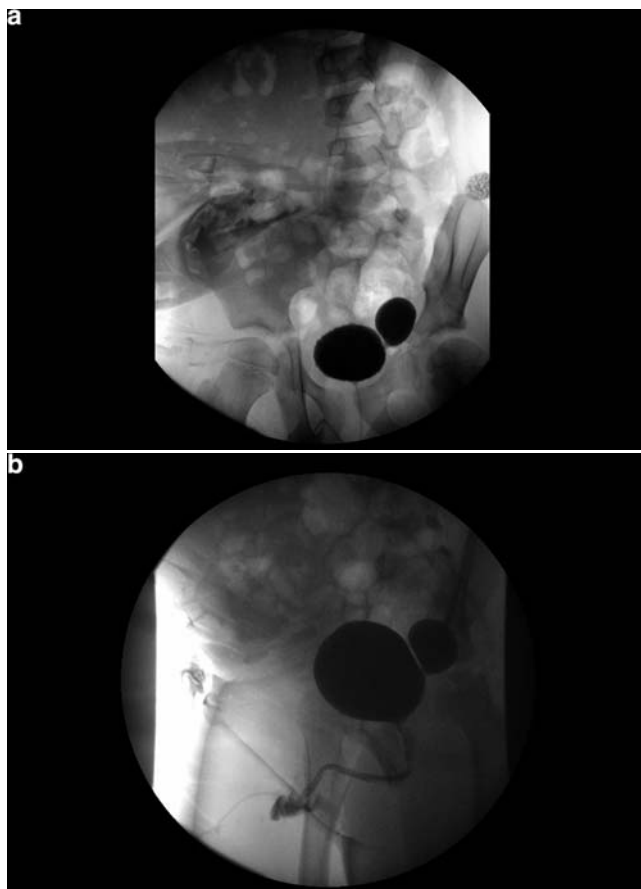
Fig. 1. VCUG demonstrating congenital diverticulum of the bladder.

Fig. 2. Isolated bladder diverticulum.
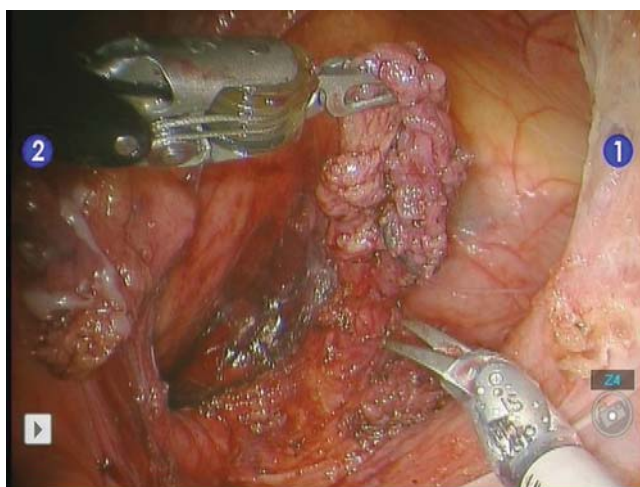
Fig. 3. Transection of diverticulum at neck.

been reported in adults *(6)*. At our institution, we have performed one robot-assisted bladder diverticulectomy

First, cystoscopy was performed and the ostium of the diverticulum is identified. A foley is then placed and clamped leaving the bladder distended. The patient is placed in a supine position. Using a Hassan technique, as 12 mm camera port is placed supraumbilically and two robotic trocars are placed lateral to the camera. A 5 mm assistant trocar is placed between the camera and left robotic trocar. The peritoneum is incised over the bladder. In a pure extravesical approach the diverticulum is dissected until the
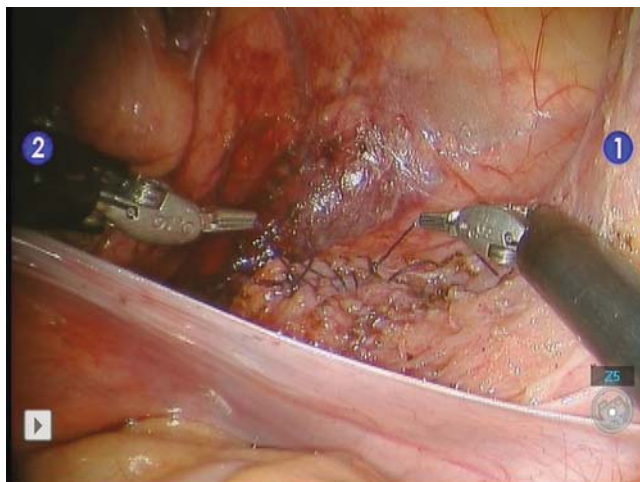
Fig. 4. Completed two-layer bladder repair.
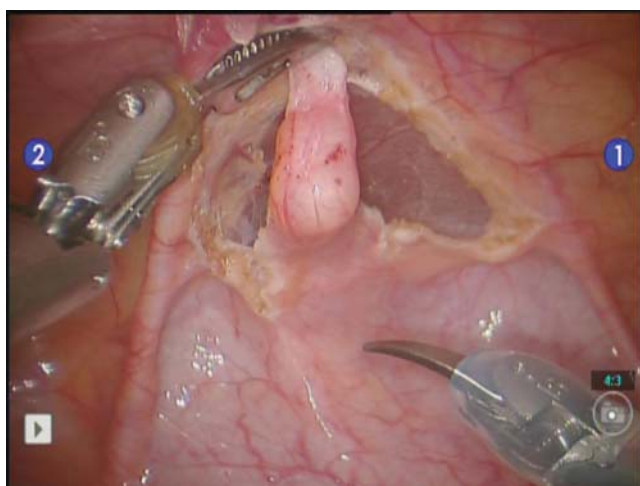
Fig. 5. Urachal cyst and bladder cuff.

neck is visualized (Fig. 1). The neck is then transected and the bladder is then closed in two layers using 2-0 Vicryl in a running fashion (Figs. 2, 3 and 4). The bladder is then filled with saline and the repair is tested. With no leak seen, no JP drain was left in place and the foley placed to gravity. There were no intraoperative or postoperative complications. Operative time was 60 minutes and EBL was 5 cc. Patient was discharged on post operative day 2 once the foley catheter was removed.
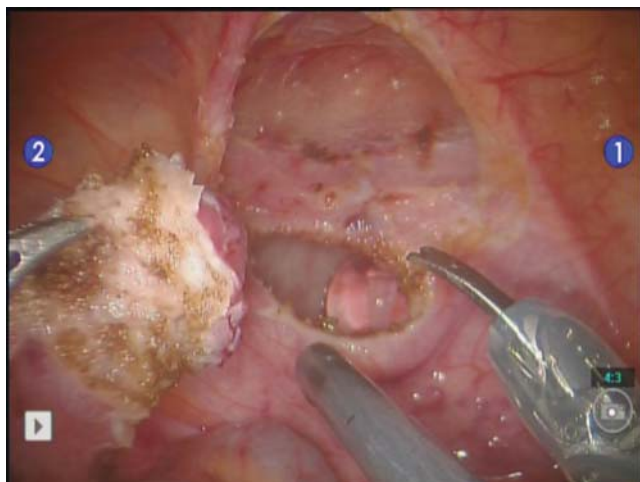
Fig. 6. Excised cyst, note foley in bladder.
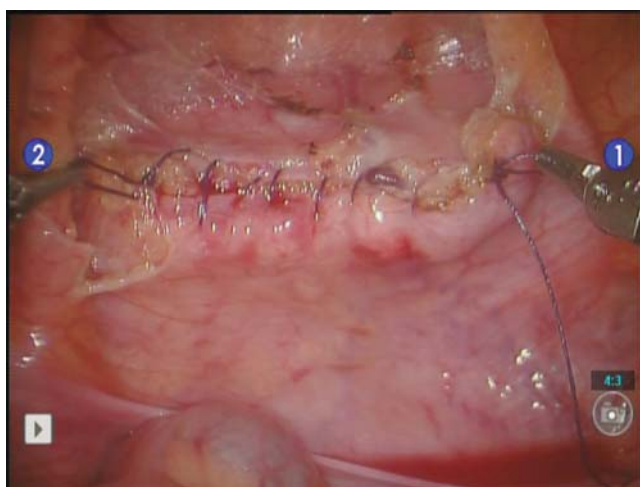
Fig. 7. Completed two-layer bladder repair.

2. URACHAL ANOMALIES

The urachus is a remnant of the allantois and is typically obliterated after birth. The urachus can remain open or become partially obliterated anywhere along its tract. Four different urachal anomalies have been described: patent urachus, umbilical-urachus sinus, urachal cyst, and vesicourachal diverticulum *(7)*. While conservative management may be indicated in asymptomatic patients due to possibility of spontaneous regression, surgery is warranted in cases of symptomatic patients or concern for malignancy. Traditionally,

this surgery has been performed as an open preperitoneal procedure. This has required a transverse or longitudinal incision with radical excision of urachal remnants along with a bladder cuff *(7)*. A laparoscopic approach has been reported as an alternative to an open procedure. Turial et al. reported a series of 27 patients who underwent excision of urachal remnants laparoscopically *(8)*. The median time of surgery was 35 minutes and there were no intraoperative or post operative complications. In this series, an initial trocar placement was an transumbilical approach. However, the authors modified their approach with lateral placement of the trocars in order to avoid injury the urachal remnant. In another series of 5 patients undergoing laparoscopic excision of urachal remnants, 2 patients developed a periumbilical hematoma and persistent drainage requiring open resection of residual tissue, respectively *(9)*. Possible advantages of laparoscopy include decreased convalenscence, improved cosmesis, and better visualization. A major disadvantage is that this technique transforms an open extraperitoneal procedure into an intraperitoneal one with possible contamination of the abdominal cavity. The use of robotic-assisted surgery for treating urachal anomalies has been reported in adults *(10)*. To our knowledge, there are no published reports of this being performed in the pediatric population. At our institution, we have performed on robot-assisted excision of urachal cyst.

First, cystoscopy was performed and a submucosal lesion was seen at the dome. A foley was then placed and clamped leaving the bladder distended. The patient is then placed in a supine position. Using a Hassan technique, a 12 mm camera port is placed supraumbically. A 5 mm assistant port is placed between the camera port and the left robotic trocar. The lesion on the dome of the bladder is visualized and using electrocauterty is circumferentially excised along with the median umbilical ligaments (Fig. 5 and 6). The bladder is then closed in two layers using 2-0 Vicryl in a running fashion (Fig. 7). The bladder is then filled with saline and the repair is tested. With no obvious leak seen, no JP drain was left in place and the foley placed to gravity. There were no intraoperative or postoperative complications. Operative time was 70 minutes and EBL was 10 cc. Patient was discharged on post operative day 2 once the foley catheter was removed. Pathology demonstrated a portion of bladder wall containing a cyst lined by colonic and anal type epithelium. The cyst contained amorphous mucoid and particulate material and rimmed by reactive lymphoid tissue.

3. BLADDER AUTOAUGMENTATION

Cartwright and Snow initially described this open surgical approach in 1989 *(11)*. The basic concept of the surgery was to excise the detrusor muscle overlying the bladder, leaving the mucosa intact and thereby creating a wide mouthed diverticulum. This results in a bladder with increased capacity and lowered filling pressure without the use of intestinal segments. First described by Ehrlich and Gershman in 1993, Braren and Bishop fol-

lowed with their experience with laparoscopic autoaugmentation in a series of seven patients *(12,13)*.Compared to pre operative cystography, there was variable increased bladder capacity from 55 to 95% on post operative cystography. In addition, 6 of 7 patients achieved complete dryness. Additional advantages may include improved cosmesis and decreased hospital stay. However, there were two intra operative complications of bladder perforation which were managed laparoscopically. A logical extension is to use robotics to improve visualization needed to create a plane between the mucosa and overlying muscle *(14)*. Cystoscopy is performed first to assess for any bladder abnormalities. A foley is placed and the bladder is left distended. The camera port and robot arm ports are placed in a similar fashion as for a robot-assisted bladder diverticulectomy. An assistant port is not used. The peritoneal reflection over the bladder is incised, allowing for exposure of the bladder dome. Using electrocautery, an elliptical incision is made into the detrusor muscle. A plane is created between this wedge of muscularis and bladder mucosa using combination of hot scissors and electrocautery (Fig. 8). This wedge of detrusor muscle is then removed through the camera port at the conclusion of the case. No JP drain is placed and the foley is placed to gravity drainage. Regardless of approach employed, proper patient selection and pre operative evaluation is needed to maximize success of this procedure. We have performed two robotic-assisted bladder autoaugmentation procedures. One patient continued to have recurrent urinary tract infections and poor compliance and will undergo ileocystoplasty.

4. RETROCAVAL URETER

Retrocaval ureter is a rare congenital anomaly due to a persistence of the posterior cardinal veins during embryologic development. Indications for intervention include decreased renal function or significant obstruction leading to flank pain, hematuria, or even nephrolithiasis. Traditionally, an open pyelopyelostomy is the standard procedure *(15)*. In a retroperitoneal approach, the dilated renal pelvis is transected and the ureter is then transposed to its normal anterior position to the vena cava. Both transperitoneal and retroperitoneal approaches have been applied to the laparoscopic management of this anomaly. While there is considerably more experience in the adult population, successful correction of this anomaly has been described in the pediatric population *(16)*. Gundeti et al. reported a single of case of a robot-assisted laparoscopic correction of a retrocaval ureter in a pediatric patient *(17)*. The patient is placed in a right lateral decubitus position and a 12 mm camera port is placed adjacent to the umbilicus. Via a transperitoneal approach, the ureter was divided and then an ureteroureterostomy was performed anterior the vena cava over a double J stent. The ureteroureterostomy was performed using 5-0 PDS in an interrupted manner. The total operative time was 180 minutes and patient had resolution of hydronephrosis at 6

months follow-up. The authors found the robot to be superior over straight laparoscopy in terms of visualization and ease of intracorporeal suturing.

5. APPENDICOVESICOSTOMY (MITROFANOFF PROCEDURE)

Appendicovesicostomy provides a continent urinary diversion in patients with a neurogenic bladder or those who are unable to catheterize via urethra. Conventionally, this is performed as an open surgery. Both pure laparoscopic and combined laparoscopic and open approach have been performed with success *(18,19)*. A natural evolution was to perform a robot-assisted appendicovesicostomy. Only a few case reports have been reported *(20–22)*. Two different locations of port placement have been described. A 12 mm camera port was placed through the umbilicus and 2 mm and 10 mm robotic ports were placed in the left lower quadrant and right midaxillary line at the level of the umbilicus. A fourth port was placed in the left midaxillary line, also at the same level for additional retraction. An additional trocar set up is with the camera port lateral to the umbilicus and the two working ports placed on the right and left at the level of the umbilicus, in the mid axillary line. The appendix is identified and the right colon is mobilized to the hepatic flexure. The appendix is separated from the cecum, preferably along with a small cuff of cecum. The bladder is incised vertically down to level of the mucosa. The appendix is then anastomosed to the bladder with 4-0 absorbable suture in an interrupted fashion. The seromuscular layer is closed with 4-0 Vicryl, creating a tunnel for the appendix. The appendix is brought to the umbilicus without tension and a catheterizable stoma is created. In one report, operative time was 6 hours without any intraoperative or post operative complications, including stomal stenosis after 10 months follow-up *(20)*.

6. MANAGEMENT OF RENAL DUPLICATION ANOMALIES

Traditionally, open surgery has been the mainstay of treatment for upper tract anomalies. Indications for intervention may include, but are not limited to, obstruction, vesicoureteral reflux, recurrent infections, ectopic ureter, and non-functioning renal moieties. As pediatric urologists gained more experience in minimally invasive techniques, they have played an increasing role in the reconstruction of complex upper tract anomalies.

Lowe et al. presented their experience with laparoscopic reconstructive surgery for patients with upper urinary tract obstruction associated with duplex anomalies *(23)*. Procedures performed included pyeloureterostomy for incomplete duplication, lower pole pyeloplasty for lower pole UPJ obstruction, and an ipsilateral uretero-ureterostomy and distal ureterectomy for an ectopic ureter. In all cases, a JJ stent was placed followed by

transperitoneal laparoscopy, in the same approach used for a laparoscopic pyeloplasty. The mean operative time was 202 minutes with a mean hospital stay of 3 days and radiologic improvement with mean follow-up of 9 months. In addition, another series of 8 laparoscopic ipsilateal ureteroureterostomies were performed in children with duplicated systems *(24)*. While there was no comparison to a similar open procedure, this technique affords improved visualization, minimal invasiveness, and possible benefits of decreased hospital stay and pain requirements.

Piaggo et al. in 2006 reported their experience in comparing open vs. laparoscopic partial nephrectomy for children with duplication anomalies *(25)*. In their series, initially there was a significant difference in operative time between the two groups. As the authors accrued more experience, this difference lost significance. Otherwise, there were comparable results between the two groups with decreased hospital stay and analgesic use in the laparoscopy group.

With the successful application of laparoscopy, the next logical step was to use the robot for treating upper tract anomalies. Pedraza et al. performed a bilateral robot-assisted heminephroureterectomy in a 4-year-old child with bilateral non-functioning upper pole segments with ectopic ureters *(26)*. Initially pure laparoscopy was used to reflect the colon medially and dissect the upper pole ureter. The robot was then used to dissect the renal hilum and upper pole vessels, and excise the upper pole segment with the use of an Argon beam coagulator and Harmonic scalpel. Overall surgical time was approximately 7 hours and the patient was discharged home on post operative day 2. In another case report, a 16-year-old female with crossed renal ectopia with fusion and an obstructed upper pole system underwent a robot-assisted ureteroureterostomy *(27)*. As with the previous case, laparoscopy was initially used to mobilize the colon. Then the robot was used to transect, transpose the ureter anterior to the crossing vessel, and perform the ureteroureterostomy. Volfson et al. in 2007 reported their total experience with robot-assisted surgery in the pediatric population *(14)*. In their series, two patients underwent robot-assisted ureteroureterostomy for complete ureteral duplication and an obstructed upper pole moiety, respectively. In these cases, the robot was used for both the initial dissection and ureteroureterostomy. One patient in this series had incontinence from an ectopic upper pole ureter (Fig. 9). This child underwent a robotic-assisted, end-to-side upper-to-lower pole uretero-ureterostomy (Figs. 10 and 11). She became continent in the immediate post operative period.

7. ROBOTIC ORCHIOPEXY

Laparoscopy plays a dual role in the management of the impalpable testicle. During diagnostic laparoscopy, both the anatomical location and appearance of the testicle can be accurately assessed. It also has a therapeutic role depending on the intra-operative findings. For diagnostic laparoscopy, a
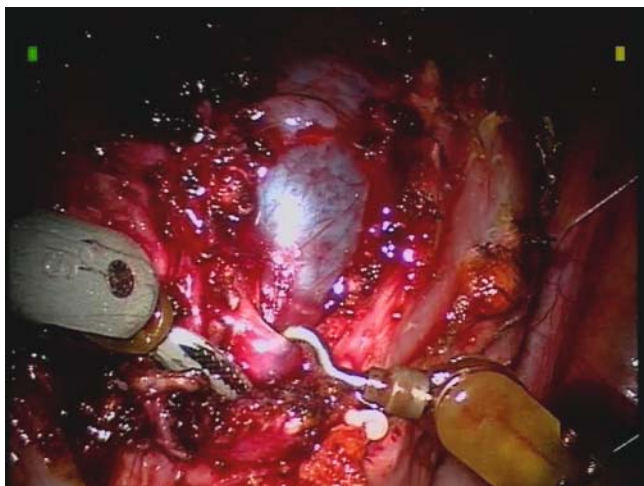
Fig. 8. Robotic hook electocautery dividing detrussor muscle.
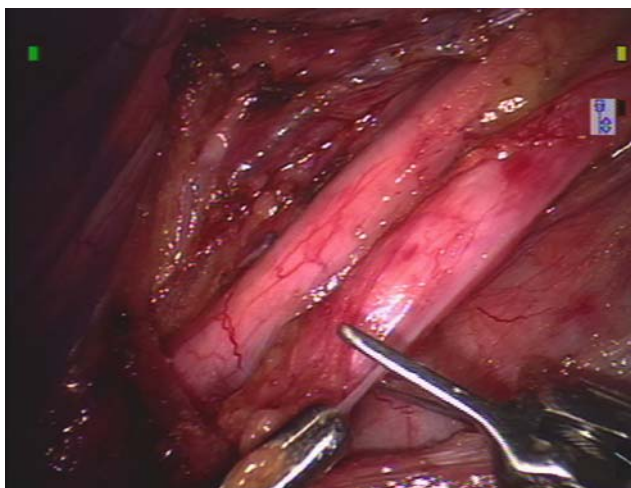
Fig. 9. Transcection of upper pole ureter.

supraumbilical 5 mm camera port is placed using the Hassan technique. Two additional 5 mm ports are placed if a laparoscopic single stage orchiopexy or first stage Fowler Stevens procedure is to be performed. The contralateral port to the undescended testis is placed at the midclavicular line at the level of the umbilicus, while the ipsilateral port is placed a few centimeters cephalad to the second port. Another configuration is with placement of the contralateral port in the lower quadrant as opposed to at the level of the umbilicus.
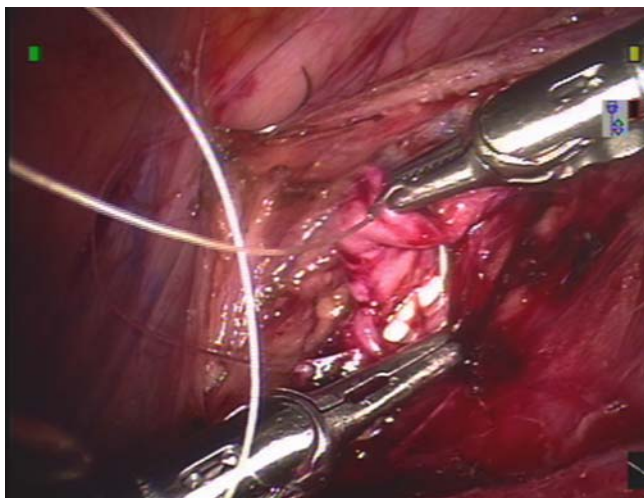
Fig. 10. 3 Fr. Stent visible in lower pole ureter. Back wall of end to side anastomosis is complete.
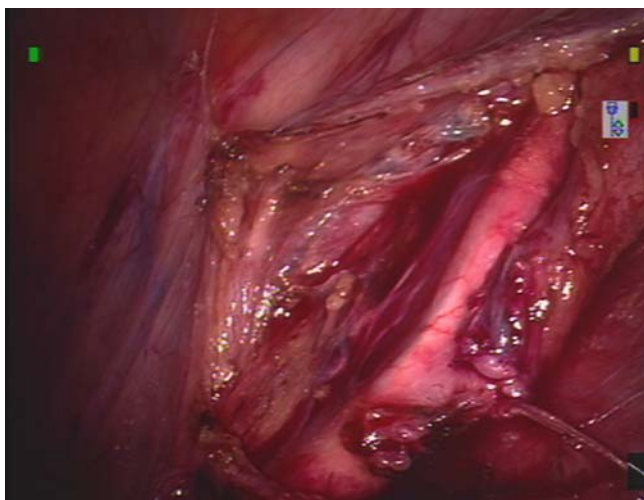
Fig. 11. Completed upper-to-lower pole end-to-side uretero-ureterostomy.

The trocar placement is similar for both the robotic and straight laparoscopic approach. For the robotic procedure, a 12 mm camera port is placed with two 5 mm robotic arm ports. A single stage robotic orchiopexy is performed in a similar manner as a conventional laparoscopic orchiopexy *(28)*. During first stage Fowler Stevens procedure, the testicle is identified and its vessels are transected. In the second stage, the peritoneum is dissected both lateral and medial to the testis and vas deferens (Fig. 12). It is crucial to create a large enough peritoneal pedicle flap to protect the medial, deferential-
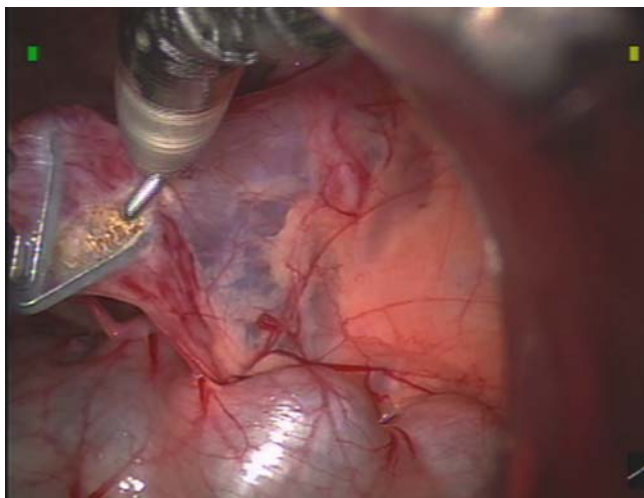
Fig. 12. One-year-old male with right intra-abdominal testicle, status post first stage laparoscopic orchiopexy. Division of previously clipped testicular artery.

based arterial blood supply. Then the testicle is mobilized ensuring tension free placement into the scrotum (Fig. 13). A dartos pouch is created and a direct passage is made from the abdominal cavity to the scrotum. The testicle is placed into the scrotum and secured. In addition, a 10 mm trocar can be placed into the ipsilateral hemiscrotum and used to create a "neo-internal ring." The trocar facilitates passage of the testicle to the scrotum (Fig. 14).
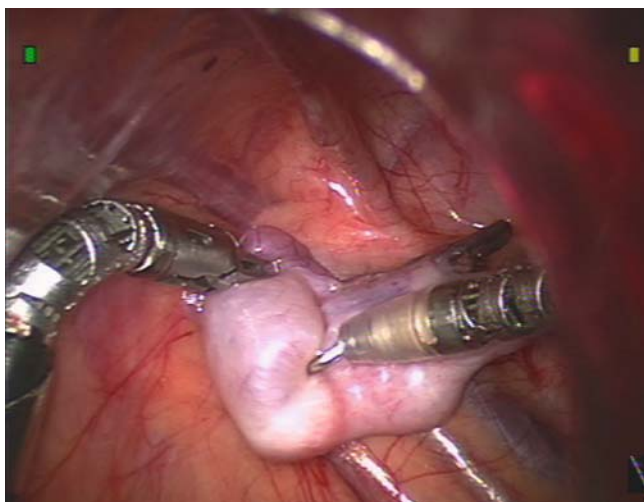
Fig. 13. Adequate mobilization determined by ability to bring testicle to contralateral internal ring.
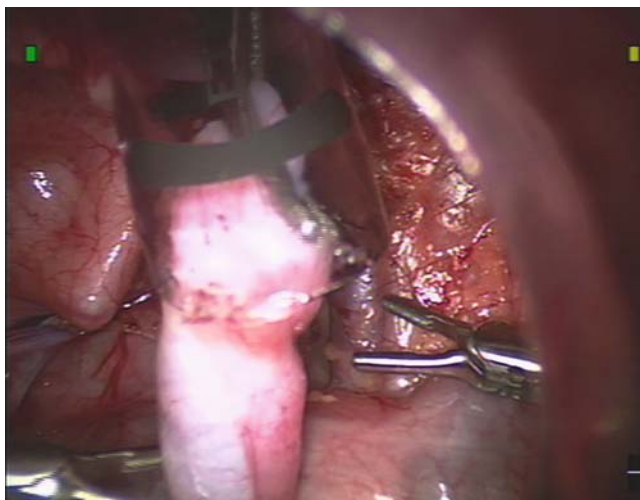
Fig. 14. Intra-abdominal testicle is delivered into 10 mm trans-scrotal trocar. Trocar protects testicle as it is pulled out of abdomen into scrotum.

Volfson et al. reported their experience with 10 robotic orchiopexies, 6 as a single stage procedure and 4 as a second stage Fowler Stevens procedure, using this technique *(14)*. Nine out of ten testes were in a scrotal position at 6 month follow-up. One patient that underwent a two-stage procedure was found to have an atrophic testicle on follow-up exam.

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14 Complications and Management of Pediatric Robotic-Assisted Laparoscopic Surgery: Prevention and Management

Ardavan Akhavan and Jeffrey A. Stock

Abstract As the application and popularity of pediatric robotic urology increases, the practicing urologist must become familiar with possible complications. While there is a dearth of literature on pediatric robotic outcomes in urological surgery, there is an even greater paucity of publications on robotic complications in children. In theory, many of the complications encountered are the same as those seen in conventional laparoscopy; however, there are a number of potential problems specific to robotic surgery that the pediatric urologist must be able to both anticipate and manage in order to minimize the risk of utilizing this novel surgical tool. The chapter summarizes the potential for and management of these complications.

Keywords Laparoscopy · Robotics · Pediatrics · Complications · Management · Urology

1. INTRODUCTION

The da Vinci Surgical System (Intuitive Surgical, Inc, Sunnyvale, CA) has had a major impact on the field of urological surgery. Fueled by increasing media attention and patient demand, minimally invasive surgeons have been enthusiastically experimenting with alternative surgical applications in fields ranging from gynecology to cardiac surgery. The advantages of magnification, increased degrees of rotational freedom, as well as 3-dimensional imaging have been particularly promising to pediatric urologists who have looked to the robot as a means of superceding the technical limitations of conventional laparoscopic surgery in children.

Over the past decade, laparoscopy has gradually become a standard of care in several pediatric urologic conditions. Diagnostic laparoscopy is indicated in the evaluation of intra-abdominal gonads in cryptorchid *(1–4)* and intersex children *(5)*. It has also been used during hernia repairs to evaluate the patency of contralateral tunica vaginalis *(6,7)*. Operative laparoscopic surgery is routinely used to perform both radical and partial nephrectomies, ureteral reimplantation, both intravesical *(8–10)* and extravesical *(11,12)*, as well as orchiopexy *(13)*. In a few centers, complicated reconstructive cases such as bladder augmentation *(14,15)* and pyeloplasty *(16,17)* are also performed laparoscopically; however, the technical difficulty associated with laparoscopic suturing has limited widespread usage of minimally invasive techniques in reconstructive cases.

The theoretical advantages of robotic surgery make it ideally suited for pediatric and reconstructive surgery: magnification allows better visualization of the fine anatomy; tremor control increases surgical accuracy; and the 360 degree rotational movement allows for greater maneuverability within limited spaces, allowing for easier suturing. However, the steep learning curve and the reluctance of most surgeons to practice on children have delayed the widespread application of this novel technology to children. Interestingly, while robotic surgery was first popularized by its urologic applications, pediatric general surgeons have been vastly more prolific in reporting their experiences with the robot than their urological counterparts. Within the urology literature, only a limited number of small series and case reports have been published documenting outcomes with pediatric robotic cases. Preliminary published outcomes suggest success rates similar to those of open surgery; however, more studies are needed before robotic surgery becomes standard of care in children.

As the application and popularity of pediatric robotic urology increases, the practicing urologist must become familiar with possible complications. While there is a dearth of literature on pediatric robotic outcomes in urological surgery, there is an even greater paucity of publications on robotic complications in children. In theory, many of the complications encountered are the same as those seen in conventional laparoscopy; however, there are a number of potential problems specific to robotic surgery that the pediatric urologist must be able to both anticipate and manage in order to minimize the risk of utilizing this novel surgical tool. The following chapter summarizes the potential for and management of these complications.

2. ANESTHETIC CONCERNS

The most obvious problem faced by anesthesiologists in robotic surgery is access. The robotic surgical cart is cumbersome and limits patient access. Proper placement of leads, monitors, and lines so that they may be accessed during the case is paramount. Many anesthesiologists recommend placement of central venous and intra-arterial catheters for monitoring central venous

pressure, blood gases, and real-time blood pressure, respectively, to recognize potential complications early [18]. Fluoroscopy may be used to verify endotracheal tube placement prior to docking. Should an airway or cardiac emergency arise, treatment would be significantly delayed by the need to undock and move the robotic cart. Prevention, communication, and preparation are essential to coordinate an emergency. Similarly, crisis simulations for operating room staff are invaluable in reducing delays in access.

The physiological effects of robotic surgery are similar to those of traditional laparoscopy; the anesthetic concerns for pneumoperitoneum and pneumoretroperitoneum are the same. However, compared with adults, children have decreased functional reserve capacity. The increased intra-abdominal pressure from pneumoperitoneum further reduces the oxygen reserve, thereby increasing airway pressures, decreasing minute ventilation and gas exchange. This is further compromised by the fact that until surgeons move beyond their learning curve, surgical time is prolonged and more CO_2 is absorbed. The hypercarbia has inotropic and arrhythmogenic effects on the heart and increases the risk of embolus, especially in children with underlying cardiac insufficiency [19]. Such children are considered poor surgical candidates for all forms of laparoscopic surgery. CO_2 emboli are evidenced by decreased end-tidal CO_2 levels and a classic mill-wheel murmur. If suspected, proper management includes rapid hemostasis, undocking of the robot, and placement of the patient in Trendelenberg in the left lateral decubitus position, followed by aspiration of the embolus through the central line [20,21] . Increased frequency of blood gas monitoring in all children is recommended. Finally, the pneumoperitoneum impairs venous return and can cause the cardiac index to fall up to 50% and cause significant edema [22]. This can be especially problematic with patients in the Trendelenburg position, as cases of resultant laryngeal edema and respiratory distress have been reported [23].

3. PATIENT POSITIONING

The animated robotic cart also has the potential to physically traumatize the patient; this is particularly worrisome in smaller children and infants, where a missed pressure point could lead to serious injury. Extra restraints and padding of pressure points and pinch areas are recommended. However, care should be taken as reports of brachial plexus neuropraxia secondary to extended positioning and padding in robotic cases have also been reported [23]. In all cases, appropriate broad-spectrum antibiotic prophylaxis, if indicated, should be administered 30 minutes prior to incision, and pneumatic compression stockings should be placed on the patient and started prior to induction and positioning. Patients should always be prepped widely in anticipation of possible conversion to an open procedure.

Patient positioning varies depending on the specifics of the surgical procedure. In general, pediatric patients are typically placed in supine

Trendelenburg position for pelvic cases. If the patient is supine, special care must be taken to pad the patient's face to prevent against trauma, endotracheal tube displacement, and airway obstruction. Extra padding around the head and shoulders should also be used to prevent any inadvertent movement and shoulder strain (Fig. 1). Padding across the chest also prevents injury from the robotic cart. The Trendelenburg position in children has been a point of physiologic concern. Regli et al. illustrated that just briefly placing children in 30 degree head-down position for placement of a central line prior to cardiac surgery resulted in a significantly decreased functional reserve capacity and lung clearance index *(24)*. Prolonged Trendelenburg positioning has also been studied. In a study looking at men undergoing laparoscopic prostatectomy for up to 4 hours, Meininger demonstrated a benign, yet significant increase in central venous pressure; heart rate, cardiac index, and systemic vascular resistance were not affected *(25)*. To our knowledge, no studies have reported on the effects of Trendelenburg positioning in robotic procedures in children.

Fig. 1. Immediate post-operative photograph of patient after robotic-assisted orchiopexy. Foam padding is used to protect the patient's face, chest, and endotracheal tube.

For renal access, the patient is placed in the lateral decubitus position (Fig. 2). The patient's hips should be aligned with the break of the operative table to allow for 70 degree flexion. In adolescents a beanbag aides in both securing the patient to the table and aligning the spine to avoid back injury or spinal trauma. We prefer using a gel pad to pad the OR table and placing an IV fluid bag behind the patient. Similarly, the lower leg should be flexed and padding should prop the upper leg to keep it in line with the spine to prevent against hyperextension, hip injury, and neuropraxia. An axillary roll should support the torso and the arms should rest tension-free on an arm

Fig. 2. Positioning and padding of 1-year-old female prior to robotic-assisted pyeloplasty.

board to prevent against brachial plexus injury. All joints and points of contact, including feet, knees, and elbows should be carefully padded to prevent pressure injuries. Care should be taken to properly secure the patient with tape and safety straps over the knees, hips, and chest to prevent inadvertent movement or repositioning. Urinary and orogastric catheterization and decompression are recommended for aiding visualization and lessening the risk of enterotomy and cystotomy *(26)*.

4. PORT SITE AND TROCAR CONCERNS

The techniques and concerns for insertion of ports are the same as those of standard laparoscopic surgery *(27)*. In 1996, Peters reported the first large-scale study of pediatric complications in urological laparoscopic surgery *(28)*. The study examined reported complications of 153 pediatric urologists during the early years of laparoscopy. Of 5,400 reported cases, there was an overall complication rate of 5.4%, the majority of which were preperitoneal insufflation and subcutaneous emphysema. Significant complications included bowel, bladder, and vascular injuries, as well as herniations, with an overall incidence of 1.18%. As expected, complications were most closely associated with surgeon experience. Additionally, method of port insertion was also strongly predictive, with closed Veress needle insertion being associated with more than twice the rate of major complications when compared to the open Hasson technique (2.55% vs. 1.19%, respectively; p < 0.006). However, open insertion is associated with a longer insertion time and a higher rate of intra-operative air leaks *(29)*. Additionally, inadvertent injury

to bowel is still a possibility during open port placement *(30)*. Body size affects the rate of injury and complications, as obese children require larger port incisions for proper visualization and insertion. The angle of insertion is also more critical in obese patients, as free mobility around ports is more limited. Conversely, thin children and smaller infants are at higher risk of bowel injury as the abdominal walls are more fragile and abdominal structures are closer to the skin. Other risk factors for injury during port site insertion include prior abdominal surgeries in the area of trocar insertion, medical comomorbidities, anatomical abnormalities, and surgeon experience.

Pediatric abdomens are obviously much more fragile than those of adults. Ports are much more likely to cause inadvertent injury to intra-abdominal structures. The decreased force necessary to penetrate the abdomen is offset by the increased risk of separating the peritoneum from the abdominal wall. This increases the risk for preperitoneal insufflation in children as well as visceral penetration. During procedures involving retroperitoneal approach, the weaker and more posterior reflection of the peritoneum makes it even more prone to inadvertent damage. Additionally, the relative size of the cannulae is much larger in children, increasing the risk of postoperative port-site hernias. Several authors recommend suturing closed all port-sites 3.5 mm in size or greater *(31–33)*.

5. REPORTED ROBOTIC COMPLICATIONS

While many large series have reported the outcomes of laparoscopic urological procedures in adults, few papers have documented the experience in children. In the robotic literature, the data is limited to a few case reports and small series. The results are summarized in Table 1. Overall, urologists have published outcomes of robotic nephrectomy, nephroureterectomy, orchiopexy, both trans and retroperitoneal pyeloplasty, bladder augmentation, adrenalectomy, appendicovesicostomy, ureteroureterostomy, as well as intra and extravesical ureteral reimplant. Other robotic procedures performed in children include pyelolithotomy, bladder neck sling, excision of Müllerian duct remnants, and sacrocolpopexy; however, the outcomes are unpublished *(34)*. Descriptions of technical operative procedures are published elsewhere *(34–37)*.

The upper urinary tract repair remains the most widely documented application of robotics in pediatric urology. There are seven papers reporting outcomes with robotic pyeloplasty over a total of 104 cases *(38–44)*. Eighty eight were done using a transperitoneal approach, 2 of which were reoperations; 16 were performed with retroperitoneal access. Of the 88 transperitoneal cases, there were a total of seven (8%) complications. These included three patients (3%) with ileus, one of which resulted in diagnostic laparoscopy. Two patients (2%) had ureteral leaks, one of which was due to a migrated stent that was managed with stent reinsertion; the other patient was treated with nephrostomy tube. Two cases (2%) were converted

Table 1
Reported Robotic Complications

Author	Procedure	Complications	Treatment
Volfson et al. (38)	Simple nephrectomy (9)	None	
	Nephroureterectomy (2)	None	
	Pyeloplasty (26)	Ileus (1)	
		Mechanical failure (1)	Exploratory laparoscopy completed with 2D imaging
	Autoaugmentation (1)	None	
	Bladder mobilization (2)	None	
	Ureteroureterostomy (2)	None	
Yee et al. (39)	Pyeloplasty (8)	Ileus (1)	No treatment
Atug et al. (40)	Pyeloplasty (7)	None	
Olsen and Jorgensen (41)	Pyeloplasty (15)	Occluded internal stent (1)	Nephrostomy tube
		Stent migration (1)	Cystoscopy and stent removal
Lee et al. (42)	Pyeloplasty (33)	Ureteral leak (1)	Nephrostomy
		Ileus (1)	
		Missed crossing vessel (1)	Reoperation with transperitoneal
Najmaldin and Antao (44)	Pyeloplasty (13)	Mechanical failure (1) inability to insert stent (1) urinary extravasation (1)	Conversion to open (2), stent reinsertion
	Nephrectomy (4)	None	
	Nephroureterectomy (4)	None	

Table 1
(Continued)

Author	Procedure	Complications	Treatment
Meehan and Sandler (49)	Adrenalectomy (3)	Hypertensive crisis (1)	Conversion to open
Pedraza (2004) (48)	Appendicovesicostomy (1)	None	
Passerotti et al. (43)	Redo pyeloplasty (1)	None	
Pedraza et al. (2004) (46)	Bilateral heminephroureterectomy (1)	None	
Passerotti and Peters (2006) (47)	Appendicovesicostomy (2)	None	
	Redo appendicovesicostomy (1)	None	
Peters (2004) and Peters (36)	Extravesical ureteral reimplant unilateral (17)	Bladder leak (1) Persistent reflux (2)	Percutaneous drain
	Extravesical ureteral reimplant bilateral (3)	Persistent reflux (1)	
	Extravesical ureteral reimplant unilateral + nephrectomy (4)	Ureteral obstruction (1)	Ureteral stent
Peters and Woo (45)	Intravesical ureteral reimplant bilateral (6)	Bladder leak (1) Persistent reflux (1)	

to open secondary to mechanical failure and inability to place the ureteral stent, respectively. Of the 16 retroperitoneal cases, there were a total of three (19%) complications, including an occluded internal stent treated with nephrostomy drainage, a migrated stent requiring stent removal, and a missed crossing vessel, resulting in a redo transperitoneal pyeloplasty. There were no complications reported with any of the redo pyeloplasties. While the numbers are small, the data does not support an advantage for retroperitoneal robotic pyeloplasty over transperitoneal.

Outcomes of robotic ureteral reimplantation have also been reported. Peters documented the only series in 2004, looking at 24 extravesical ureterocystostomies, three of which were bilateral, and four that included a contralateral nephrectomy (37). Of the unilateral patients, one (5%) suffered from a bladder leak postoperatively, treated with a percutaneous drain, and two (10%) had persistent low-grade reflux. One (33%) of the three patients with bilateral repair had persistent reflux. One patient (4%) suffered from ureteral obstruction, treated with ureteral stent. In 2005, Peters also reported his experience with intravesical ureteral reimplantations (45). Out of six cases, one (18%) suffered from a bladder leak from insufficient port site closure, and another (18%) had recurrent low-grade reflux. Given the vesical space needed to maneuver, the procedure is not recommended for children with bladder sizes less than 130 ml (34).

There have been relatively few reports of robotic nephrectomies in children, mostly due to the relatively rare indications for such a procedure in children. Not including nephrectomies performed in conjunction with ureteral reimplantation, there are a total of 13 simple nephrectomies, six nephroureterectomies, and one bilateral heminephroureterectomy reported in three articles (38,44,46). No complications have been reported.

Novel applications of robotics have been reported in sporadic case reports. These include two authors' experiences with a total of four appendicovesicostomies, one of which was a redo operation with no complications (47,48). Three cases of robotic adrenalectomy for pheochromocytoma have also been reported (49). One patient (33%) suffered intra-operative hypertensive crisis and the case had to be converted to open. Other case reports include a single report of intracorporeal bladder autoaugmentation and two reports of bladder and bowel mobilization for extracorporeal manipulation, all without any reported complications (38). The same group also reported experience with robotic ureteroureterostomy. One of their cases was complicated by mechanical failure with loss of 3-dimensional imaging and color; the case was completed robotically.

6. PERSISTENT PNEUMOPERITONEUM

Postoperatively, persistent pneumoperitoneum is a known complication of both open and laparoscopic surgery. Morbidity occurs when it is misidentified as an enterotomy and the patient undergoes needless exploratory

surgery. While there are no studies examining persistent pneumoperitoneum either in robotics or in children, the finding has been extensively reported in adults. Most authors demonstrate resolution of the free air within a week; however, case reports have documented air on plain films 5 weeks after laparoscopic surgery *(50)* and 8 weeks following open procedure *(51)*. Associations with operative time, gender, body mass index, and open vs. laparoscopic technique are debatable depending on the report. We recommend the finding of free air be correlated clinically with such indices as abdominal pain, physical exam, and leukocytosis before the patient is taken back to the operating room.

7. CONVERSION TO OPEN

The indications for converting a robotic procedure to an open are the same as those for laparoscopy, namely equipment failure, uncontrollable bleeding, and failure to progress. While the first two points are easy to determine, the last indication is a subjective decision. Given the increased perioperative morbidity associated with prolonged anesthesia and pneumoperitoneum, the surgeon should start each case with defined criteria for progression and be cognizant of when conversion would benefit the patient. Preoperative drills detaching and moving the robotic cart with the surgical team are essential in minimizing delays in case of emergent hemorrhage. Each patient should already be prepped preoperatively in anticipation of possible conversion, and all surgical instruments should be sterilized and immediately available.

8. CONSENT

To date, pediatric robotic surgery is still in its infancy. Primary outcomes and limitations are still being defined. While a handful of high-volume academic urologists have published promising outcomes, the vast majority of pediatric urologists are still on the steep portion of the learning curve. In addition to explaining reported success rates, when obtaining consent surgeons must be sure to explain the novel nature of the technology and personal experience, including number of cases performed, average operative time, conversion to open, and rates of major complications with open, laparoscopic, and robotic modalities. There may be a tendency for inexperienced surgeons to persuade patients to elect for a robotic procedure to increase console experience; however, optimal treatment for the patient and informed consent are paramount. Patients must be carefully screened for the procedure, especially while the surgeon is still refining his technique, and the parents must understand the longer operative time and risk of conversion and complications while the surgeon is still learning.

9. CONCLUSION

Robotic surgery is quickly changing the landscape of minimally invasive pediatric urology. The limitations of laparoscopic surgery are extended dramatically by the increased degrees of intracorporeal freedom and greater visual magnification afforded by the robotic instrument. Robotic surgery in children is still in its infancy, and a great deal more experience is necessary before establishing more reliable complication rates and guidelines.

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Note: The letters '*f*' and '*t*' following locators refer to figures and tables respectively.